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NASA Contractor Report 3396

Satellite Power Systems (SPS) Concept Definition Study (Exhibit D)

Volume V - Systems Engineering/Integration Research and Technology

G. M. Hanley

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Volume V - Systems Engineering/Integration Research and Technology

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Prepared for
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FOREWORD

Volume V, *Systems Engineering/Integration, Research and Technology*, of the SPS Concept Definition Study final report is submitted by Rockwell International through the Space Operations and Satellite Systems Division. All work was completed in response to NASA/MSFC Contract NAS8-32475, Exhibit D.

The SPS final report provides the NASA with additional information on the selection of a viable SPS concept, and furnishes a basis for subsequent technology advancement and verification activities. Other volumes of the final report are listed below.

<u>Volume</u>	
I	Executive Summary
II	Systems/Subsystems Analyses
III	Transportation Analyses
IV	Operations Analyses
VI	Cost and Programmatics
VII	Systems/Subsystems Requirements Data Book

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ILLUSTRATIONS

TABLES

GLOSSARY

A	Ampere
Å	Angstrom
ac	Alternating current
ACSS	Attitude control and stationkeeping system
AMO	Air mass zero
ARDS	Attitude reference determination system
$\overline{B}$	Billions of dollars
B_eO	Beryllium oxide (Berlox)
BCD	Binary coded decimal
BCU	Bus control units
BOL	Beginning of life
BT	Battery tie contactor
°C	Degree centigrade
C_e	Cesium
cm	Centimeter
CMD	Command
COTV	Cargo orbital transfer vehicle
CPU	Central processing unit
CR	Concentration ratio
CR_E	Effective concentration ratio
CVD	Controlled vapor deposit
D/A	Digital to analog
dB	Decibel
dc	Direct current
DOE	Department of Energy
DVM	Digital voltmeter

EBS	Electron beam semiconductor
E_g	Bandgap energy
EMI	Electromagnetic interference
EOL	End of life
EOTV	Electric orbital transfer vehicle
EVA	Extra-vehicular activity
f	Frequency
°F	Degree Fahrenheit
FEP	Adhesive material
FET	Field-effect transistor
FOC	Final operational capability
f_p	Pilot frequency
fr	Reference signal frequency
f_T	Transmitted frequency
G	Giga- (10^9)
G	Gear, switch
GaAlAs	Gallium aluminum arsenide
GaAs	Gallium arsenide
GEO	Geosynchronous, equatorial orbit
GHz	Gigahertz
GPS	Global Positioning System
GRS	Ground receiving station
GW	Gigawatt
HLLV	Heavy-lift launch vehicle
HPWB	Half-power-point beamwidth
HV	High voltage
Hz	Hertz
IB	Interface bus
IBM	International Business Machines Corp.
IMCS	Information management and control system
IMS	Information management system (see IMCS)

IOC	Initial operations capability
IOP	In-orbit plane
IOTV	Inter-orbit transfer vehicle
IUS	Inter-orbit utility stage
k	Kilo (10^3)
K	Potassium
°K	Degree Kelvin
km	Kilometer (1000 meters)
kN	Kilonewton
KSC	Kennedy Space Flight Center
kV	Kilovolts
LED	Light-emitting diode
LEO	Low earth orbit
LH_2	Liquid hydrogen
LOX	Liquid oxygen
LPE	Liquid phase epitaxal
LRB	Liquid rocket booster
LRU	Line replaceable unit
LSST	Large space structures technology
m	Meter
M	Mega- (10^6)
MBG	Multi-bandgap
MC-ABES	Multi-cycle airbreathing engine system
MeV	Millions of electron volts
μp	Microprocessor
MPCA	Master phase reference control amplifier
MPTS	Microwave power transmission system
MSFC	Marshall Space Flight Center
MTBF	Mean time between failure
MTTF	Mean time to failure
MW	Megawatt
MW	Microwave

MW_e	Megawatt—electrical
MWM	Manned work modules
MW_T	Megawatt—thermal
M_x	Disturbance torque along X-axis
N	Newton
NaK	Sodium-potassium
NASA	National Aeronautics and Space Administration
N-S	North-South
O&M	Operations and maintenance
OTV	Orbit transfer vehicle
PDS	Power distribution system
PLV	Personnel launch vehicle
PM	Personnel module
POP	Perpendicular to orbit plane
POTV	Personnel orbital transfer vehicle
psi	Pounds per square inch
RAC	Remote acquisition and control
R&D	Research and development
R&T	Research and technology
RCA	Radio Corporation of America
RCI	Replacement cost investment
RCR	Resonant cavity radiator
RCS	Reaction control system
RF	Radio frequency
RFI	Radio frequency interference
RTE	Real-time evaluation
S/A	Solar array
SCB	Space construction base
SG	Switch gear
Si	Silicon

SIT	Static induction transistor
SM	Sub-multiplexer
SOC	Space Operations Center
SPS	Satellite Power Systems
SRB	Solid rocket booster
STS	Space Transportation System
T	Temperature
TBD	To be determined
T&E	Test and evaluation
TFU	Theoretical first unit
TT&C	Telemetry, tracking, and communications
TWT	Traveling wave tubes
UI	Utility interface
V	Volt
VHF	Very high frequency
VSWR	Voltage standing wave ratio
VTO	Vertical take-off
W	Watt
Wh	Watt-hour
X,Y,Z	Coordinate axes of satellite

Symbols

ε	Error signals
λ	Wavelength of frequency f (Hertz)
μ	Micro-
η	Efficiency
ϕ	Phase
Φ	Coordinate axis angle—Phi
θ	Coordinate axis (angle)—Theta

1.0 INTRODUCTION AND OBJECTIVES

1.1 INTRODUCTION

Studies of the Satellite Power System (SPS) concept have attested to the technical feasibility of solar power stations located in space and to their potentially economic advantages as compared with candidate earth-based energy systems in the calendar period, 2000-2030. Although overall success of SPS development is possible over a range of performance and design levels, it is necessary to define attainable performance parameters for the development of SPS specifications and design requirements through a confirmation of technology advancement requirements.

In order to continue with various SPS concept definition studies, knowledgeable extrapolations of the current state of technology, the degrees of improvement in technical performance, and the expected reductions in cost all require further analysis to identify the degree of technical risk. On this basis, planned experiments and exploratory technology development activities would reduce this uncertainty and improve the levels of confidence for system design.

This volume defines just such a series of requirements. This section of the report presents guidelines and ground rules followed in the development of requirements for the SPS. Development planning objectives are specified in each of these areas and evolutionary SPS program scenarios are described for the various concepts studied during this past one-year contract.

Program descriptions are presented as planning packages of technical tasks, schedule phasing, and associated cost estimates. Each package identifies the ground-based technology effort that will facilitate SPS definitions, designs, development, and operations.

1.2 SCOPE OF EFFORT

Earlier Rockwell studies associated with technology advancement also focused on development activities.[1] During the current contract period, this series of guidelines and ground rules was updated and maintained for the uniform development of SPS programmatic results. These guidelines/ground rules are as follows:

- SPS initial operational capability is in the year 2000
- A program buildup over 30 years to provide a total of 300 GW at the utility interface by the year 2030

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[1]*Satellite Power Systems (SPS) Concept Definition Study—Experimental Verification Definition*, Rockwell International Corp., SSD 79-0010-3 (March 1979).

- Key dates of program planning:

1981-1986	Research and Technology
1981-1987	Key Technology Program Activities
1990	Decision Point for SPS Commercialization
2000	IOC of first SPS

- Satellite construction and assembly to occur at geosynchronous orbit
- Overall SPS lifetime will be 30 years with maintenance
- Activities done to definitely allow a go or no-go decision to the next phase
- Rely on other technology activities and support programs as much as possible to maximize required knowledge
- Consider all viable system and subsystem alternatives to increase success in solving key problems
- Costs to be in 1979 dollars
- A funding plan shall be developed for all technology efforts

1.2.1 TECHNOLOGY PLANNING

In 1978, the Rockwell SPS team conducted a review of DOE, NASA, and contracted studies to update key areas of technology planning. This review and subsequent internal Rockwell analyses resulted in a number of issues covering the spectrum of SPS activities. These items were consolidated into a complete list that became an initial data base (Figure 1.2-1) from which to align the most critical issues and technical requirements.

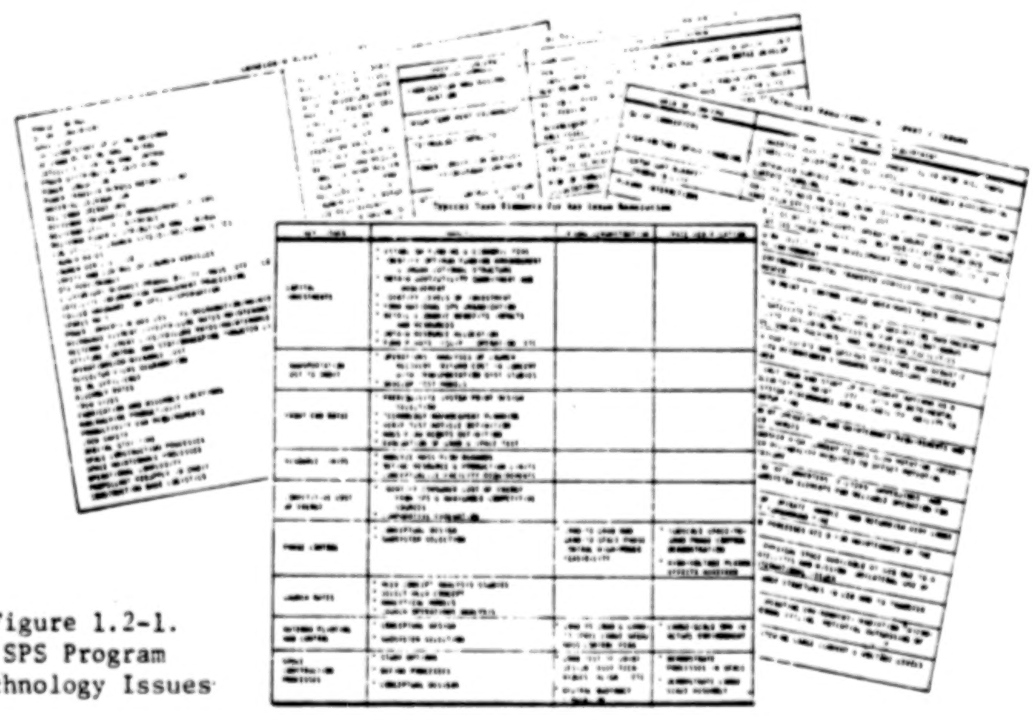

Figure 1.2-1. SPS Program Technology Issues

The program philosophy for resolution of these issues was to categorize each item into three categories covering the activities of analysis, ground demonstration, and space verification. Since it is known that each succeeding step becomes more costly, the approach was to obtain the maximum benefit at lower steps.

Each issue was then studied independently, and an effort devoted toward the definition of a top-level sequence of events that would lead to the resolution of that issue. Later, these issues were integrated into a composite verification program by category. As some of the issues can essentially be resolved with analyses, they will not require ground or space verification. For example, issues of capital investments can be resolved by analyses. Certainly ground and space verification of components, subsystems, and systems will contribute indirectly by increasing confidence in the SPS program and thereby help to secure the necessary capital for financing materials, equipment, etc. However, direct contribution to resolving the issues will be accomplished through analyses.

Other issues can be resolved by a combination of analyses and ground demonstration; for example, the issue of solar cell cost can be resolved without going to space. On the other hand, there are some issues which cannot be satisfactorily resolved without utilizing space verification. Relatively little is known about orbital assembly requirements, techniques equipment, etc., that will be needed for orbital assembly of the large spacecraft. There are several questions that cannot be satisfactorily resolved by analyses and ground demonstration due to the unique environment (zero gravity, low vacuum, thermal cycling, etc.) of space.

Activities associated with technology advancement include the ground-based exploratory development period and the resolution of remaining technology issues requiring space flight experimentation and testing. On this basis, a series of objectives were established for the SPS development planning activity, as shown in Table 1.2-1.

Table 1.2-1. SPS Research and Technology Planning Objectives

✓ Structure a synthesized SPS development plan that

- Acknowledges key technology issues and areas of concern as structured within elements of SPS system definition.
- Emphasizes ground-based research and technology.
- Illustrates operational sequences leading to successful SPS IOC --ground, orbital—mass transfer.
- Recognizes DOE/NASA environmental studies, SPS evolutionary development, and NASA fiscal planning.

✓ Evaluate development plan requirements to:

- Minimize front-end costs
- Maximize ground-based testing
- Utilize Shuttle and Space Base capabilities to maximum
- Reflect reasonable lead times
- Establish optimum program planning for precursor verification and SPS confirmation.

1.2.2 TECHNOLOGY ANALYSES

The next step was to combine key issues and system elements in a tree-like structure of technology considerations and areas requiring further definition and exploration. Rockwell SPS requirements, current NASA documentation, and other supporting information were reviewed to update technology needs and to identify the levels of criticality on various subsystems. As a result of these analyses, the series of "trees" reaffirmed options and potential alternatives for technology advancements pertinent to a particular field. Figure 1.2-2 presents some of the structures that have served as a guide, or road map, to the period of technology investigation. Tasks were then identified in these areas for the development and advancement of promising SPS technology. This was done in an iterative manner and documentation contained in subsequent sections explains these investigatory procedures and technology requirements.

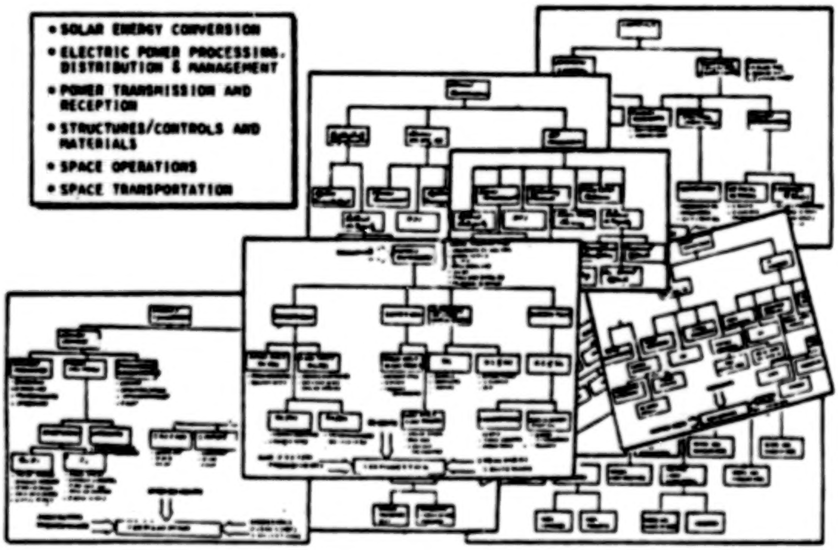

Figure 1.2-2. Subsystem Technology Options

In order to attain indicated objectives, the technology and development planning effort identified requirements of SPS systems and subsystems that were grouped into the following areas:

- SPS System Definition Studies
- Solar Energy Conversion
- Electric Power Processing, Distribution, and Management
- Power Transmission and Reception
- Structures/Controls and Materials
- Space Operations
- Space Transportation

<u>SPS System Definition Studies</u>

The primary objective of this effort is to maintain a record of SPS technology requirements on the current Rockwell reference configuration. It will serve in the evaluation and comparison of alternative systems and be available

for use by others in completing their SPS tasks (i.e., environmental, comparative, and societal assessments). This work will be compatible with the overall SPS Research and Development (R&D) plan, where the essential function is to translate technology improvements and/or test and analysis results into system/program-level technology considerations with defined cost, performance schedule, and resource requirements. Both SPS ground and space flight efforts will be acknowledged.

Solar Energy Conversion

The objective of work in this area is to define and develop component and subsystem technologies for an advanced photovoltaic conversion subsystem, solar cells, solar array blankets, and concentrators, along with a definition of associated ground and space flight tests for technology verification leading to production. Cost, schedule, and resource requirements will also be defined.

Electric Power Processing, Distribution, and Management

Technology requirements and analyses will be established for electric power distribution and conditioning systems including processors, switch gears, rotary joint, power conductors, and energy storage systems. Ground tests and space environmental effects programs will be identified. Cost, schedule, and resource requirements for these systems and test/verification programs will be described along with breadboard/engineering models for integrated performance evaluation.

Power Transmission and Reception

The objective of this project is to identify critical early analyses and exploratory technology relating to microwave energy transmission/reception. Issues will address critical component definitions relative to microwave power amplification and transmission, phase control system, and ground power rectification, emphasizing initial definitions of microwave ground test range requirements and characteristics. Computer simulation modeling, experimental lab development, and engineering model evaluations will be outlined as they lead to space tests/verification.

Structures/Controls and Materials

The objective of this project area is to determine the feasibility and technology requirements of structural dynamics and flight control system concepts for SPS and to characterize materials suitable for SPS applications. This activity will include the development of math models for simulation of the dynamics and active control system. These models will be integrated into a ground test program that should be conducted to verify simulation tests. These ground tests will provide basic information to the analyses and definition of system requirements and the verification of flight control system performances.

Candidate materials and applications will be studied, tested, and evaluated to characterize the material and processes proposed for SPS structures, subsystems, and components.

Space Operations

The overall objective of projects in this category is to demonstrate feasibility of high productivity in space construction through test, analysis, and evaluation of critical construction equipment concepts and techniques. This effort covers three areas—operations and support functions, structure fabrication and assembly, and system installation.

Space Transportation

Technology issues will be identified and investigated to establish the technical and economic feasibility of transportation concepts being considered for the SPS. The approach will include a broad-based investigation of rocket and airbreathing propulsion, thermostructure, cryogenic insulation, electric propulsion, ballistic booster recovery, analytical tool development, and operational techniques—such that a mature, compatible data base will exist at the time of heavy-lift launch vehicle (HLLV) concept selection.

2.0 TECHNOLOGY DEVELOPMENT PLANNING

2.1 INTRODUCTION

SPS technical and programmatic studies have identified a need to reduce technological uncertainties in the various subsystem areas that would lead to a cost-effective program with reduced risk. A dedicated effort of research and development (R&D) during the next six years offers potentially significant advantage to the resolution of issues, the development of a preferred SPS system concept, and the lowering of front-end costs.

Based on current subsystem technology analyses, the results of recently completed NASA technology workshops, and the conclusions of earlier development planning approaches, two major technology development scenarios were prepared to reflect the sequence of activities applicable to SPS concepts studied under Exhibit D. Activities associated with these scenarios emphasized technology advancement and engineering verification plus proof of concept.

Phases of the technology advancement and SPS precursor development plan includes a series of steps intended to validate research and development assessments and confirm SPS design/performance expectations. These phases are the underlying theme of the R&D scenario:

- Research and Technology
- Shuttle and Space Operations Center Utilization
- Hexagonal Frame Structure as Demonstration Article
- SPS Pilot Plant
- LEO/GEO Test Verification
- Ground Systems Support

SPS precursor designs for the required period will incorporate (1) the results of an agressive program for the selection of preferred concepts and subsystem definitions; (2) space test sequences to validate satellite and ground system performances; (3) simulations representative of those expected in a full-up end-to-end demonstration; and (4) prototypical examples of ground-based requirements, mass flows to orbit, and space construction operations.

R&D/verification planning and analysis were, therefore, directed toward the integration of these evolutionary phases and their consistency with stated objectives.

2.2 RESEARCH AND DEVELOPMENT

Elements of the R&D phase extending through 1986 were studied and documented for each of the principal areas of technology advancement. Early analyses and experimental/research tasks are essential ingredients of the requisite proof of feasibility for critical issue technology elements of the SPS system. Establishment of firm designs, performance levels, development

requirements, cost and efficiency trades, and system environmental acceptability all depend on early verification of the achievable characteristics of many critical subsystem components.

R&D research and technology tasks applicable to SPS baseline configurations have been prepared to update prior technology assessments incorporating information from DOE/NASA workshops. (A detailed explanation and task description, along with schedule and funding projections, are presented in subsequent sections.) The following paragraphs summarize proposed SPS supporting research and technology with an emphasis on R&D activities of the period through 1986.

2.2 RESEARCH AND DEVELOPMENT

2.2.1 SYSTEM DEFINITION

The objectives of systems definition and planning are to provide for the integration of subsystems and systems into a preferred SPS concept, and to assess candidate alternative concepts responsive to the results of environmental, societal, and comparative assessment impacts on system design. This includes the consideration of economic viability and the benefits of other emerging technologies to the SPS concept. It encompasses development plans for the orderly transition of research and development plans for the orderly transition of research and development to SPS commercialization.

The essential function to be performed in the near term is to translate technology improvements and/or test and analysis results into system/program-level technology considerations with defined cost, performance schedule, and resource requirements of both ground and space flight programs.

Tasks associated with this area are:

- System Integration
- Alternate Concept Assessment
- Technology Impacts on System Design
- Environmental, Societal, and Comparative Assessment Impacts on System Design
- System Analysis and Planning

Three additional tasks, discussed essentially in the Space Transportation section are:

- Advanced Engine Concepts
- Electric Orbital Transfer Vehicle Definition
- Personnel Orbital Transfer Vehicle Definition

2.2.2 SOLAR ENERGY CONVERSION IN SPACE

The objective of this program is to identify, research, and develop the component and subsystem technologies for an advanced solar energy conversion subsystem to support future SPS design and tradeoff studies. A GaAs photovoltaic subsystem has the potential of low weight, high efficiency, higher resistance to ionized radiation levels, and the ability to operate with concentrators under high temperature with a minimum loss in performance.

The attainment of a set of certain design parameters for the conversion system is critical to assuring SPS cost viability, and the proof of feasibility of attaining these design parameters is necessary.

It is recommended that investigations be continued of advanced concepts that offer potential of significant advances in performance, mass, and/or cost of the photovoltaic energy conversion system over the "reference" concepts and designs. New system studies should be conducted to re-evaluate concentration ratio and evaluate new developments to provide an even more optimistic perspective for SPS for additional technological "breathing room" for the concept. A task summary follows:

- Basic Solar Cell Research and Development
- GaAs Solar Cell Qualification Program
- Solar Array Demonstration Program
- Accelerated 30-Year-Lifetime Testing
- Manufacturing Processes Analyses and Cost Evaluation
- Multi-Bandgap Thin-Film Solar Cell Research and Development
- Alternate Advanced Concept Evaluation

2.2.3 ELECTRIC POWER PROCESSING, DISTRIBUTION, AND MANAGEMENT IN SPACE

The primary objective of this early research is to establish technical feasibility and economic practicability for high-voltage space operations of the SPS satellite. Technical feasibility will depend on the technology readiness of techniques, components, and equipment to reliably distribute, process, and interrupt hundreds of megawatts of power at tens of thousands of kilovolts. Minimum-weight power processors and power conductors are required. The combined requirements of dissipating concentrated heat and preventing breakdown or arc-overs are much more severe in space than in similar high-power and high-voltage ground applications. The SPS spaceborne power distribution and processing concepts depend upon successful realization of high-power kilovolt ultrafast protection switches.

Consideration should be given to the spaceborne PDC requirements of alternatives to high-voltage transmission tubes, such as solid-state dc-RF converters.

Tasks associated with this area follow:

- Requirements Definition Study
- Laboratory Experimentation and Feasibility Test Models
- Spaceborne Power Devices R&D
- Spaceborne Power Transmission R&D
- Rings and Brushes Materials R&D
- Study of Plasma Effects and Laboratory Tests
- Molten Salt Electrolyte Battery Design
- System Operations

2.2.4 MICROWAVE POWER TRANSMISSION IN SPACE AND GROUND RECEPTION

The objective of this effort is to conduct critical early analyses and exploratory technology relating to microwave energy transmission from space and ground reception key technical issue resolution and fundamental technical feasibility. The tasks in this plan address critical component definition issues relative to microwave power amplification and transmission, ground power rectification and initial definition of microwave ground test range requirements and characteristics. Computer simulation modeling, experimental lab development, and engineering model evaluation will be performed. Specific task plans cover:

- Ground test range definition
- 50-kW klystron and 5- to 10-kW magnetron definition
- RCR concept evaluation
- MPTS antenna pattern calculation, alternate concept technique investigation, and power dipole optimization
- GaAs diode concept evaluation
- Power transistor preliminary definition
- Phase control system
- RF signal distribution system development
- High-gain rectenna element development
- High-gain pilot receiver antenna development
- Pilot transmit system study and concept development
- Study of alternate sensing techniques
- Study of aperture distribution functions, beam steering, and associated problem areas

2.2.5 STRUCTURES, CONTROLS, AND MATERIALS

The objective of this experimental research is to develop technology associated with specific aspects of the structural subsystem of the in-orbit portion of a Satellite Power System (SPS). Optimum structural element shapes will be developed based on design, analysis, and test data. Advanced composite material systems will be selected for satellite structures, applications, and mechanical properties of those systems to be developed. (Mathematical simulations of SPS configurations utilizing test-determined stiffnesses, damping valves, etc., will be generated and subjected to simulated operational environments to determine as-designed structural integrity including operational stress levels and satellite distortions.) Satellite structure construction scenarios will be generated, construction equipment defined and conceptually designed, and a plan generated for the ground and on-orbit technology development of this equipment. (Attitude and figure control technology and ACS propulsion system research are also included in this effort.) A task summary follows:

Space-Located Structures and Materials

- Construction selection and structural requirements
- Composite materials R&D
- Machine-made beam R&D
- Beam-to-beam joining
- Ultra-large solar blanket/reflector arrays
- Solid-state sandwich R&D
- Mathematical model development

Controls

- Ion thruster and power module laboratory testing
- EOTV attitude and thrust vector control
- Figure control techniques and systems
- Control system development and hardware requirements
- ACS electric propulsion R&D

2.2.6 SPACE OPERATIONS

The objective of this category is to acknowledge elements comprising space operations and to describe tasks associated with their completion during the period of 1981-1986. Developing the capability for construction and assembly of large low-density structures in space is an inherent requirement for the SPS program. The capability for installation of other subsystems (e.g., solar blankets, reflectors, power distribution lines and control equipment, microwave subarray hardware, etc.) on the structure must also be developed. Very little applicable data currently exist for this type of orbital and large-scale terrestrial construction and assembly. Test data are needed to validate operational requirements and cost estimates. Tasks will cover the areas of automated construction, operations and support, and hardware handling and installation.

2.2.7 SPACE TRANSPORTATION

The objective of this effort is to conduct critical early analyses and exploratory technology relating to the various transportation system elements, key technical issues resolution, and fundamental technical feasibility. The tasks in this plan address critical systems and subsystems issues relative to earth to low-earth orbit and orbit-to-orbit transfer vehicles for both cargo and personnel. The transportation elements considered in this plan include a Space Transportation System (STS) derived heavy-lift launch vehicle (HLLV), dedicated SPS HLLV configuration, an electric orbital transfer vehicle (EOTV) for cargo transfer, and a personnel orbital transfer vehicle (POTV) for personnel/priority cargo transfer from LEO to GEO and return. Systems and subsystems studies, computer analyses and modeling, experimental laboratory development, and engineering model evaluation are to be performed. Main tasks include:

- Heavy-Lift Launch Vehicle Definition
  - Structural/thermal protection systems
  - Propellant tank insulation systems
  - Liquid rocket engine component life improvement
  - LOX [illegible] attitude control systems
  - Self monitoring/diagnostic systems

2.2.8 AIRCRAFT FLIGHT TESTS

It is also anticipated that in conjunction with or immediately following R&D, aircraft flight testing may be required to validate some of the techniques which were defined during the ground-based research effort. Although the Shuttle would be available during this period, it may not necessarily be cost effective to perform the test from space.

As an example, aircraft tests appear warranted in the investigatory research of optimum frequencies, slant range effects, atmospheric limitations, processing techniques, and transmitter/receiver signal-to-noise accuracy relationships pertinent to the pilot receiver/transmitter used between the SPS and rectenna. These tests would be conducted prior to the definition of articles for space testing. In this manner, repeatability of phase relationships would be defined and the effect of any demonstrated non-repeatability on power transfer could be analytically determined. Full-blown testing, including power transfer, would be conducted during the proof-of-concept effort.

2.3 SPACE TRANSPORTATION SYSTEM (STS)

Transportation elements of the program are key to the development and construction of an operational precursor satellite and the economic transfer of required materials and personnel to orbit in the pre- and post-1990 period.

Several transportation system variations are being considered for use during the late R&D period and during subsequent years of precursor development. They include (1) a normal version of the STS with solid rocket boosters and a Titan core modification, (2) a growth STS version that replaces the solid rocket boosters (SRB) with liquid rocket boosters and uses a personnel launch vehicle integral with the orbiter, and (3) a derivative STS-HLLV with a liquid rocket booster that would be used for cargo placed in a payload container with special engine module to replace the orbiter. Subsequent development of the SPS-HLLV would be used to deliver mass to orbit in the late 1990's for the movement of greater mass-to-orbit requirements.

2.4 SPACE OPERATIONS CENTER

Many concepts of space construction and support are suggestive of the variety of space base configurations undergoing study as to concept and operation. These studies have ranged from the use of an STS orbiter[1] as the construction base to a more recent study of a space operations center (SOC).[2]

Results of the Space Construction System Analysis contract identified an evolutionary development plan of requisite technology, potential equipment design requirements, and support system needs to construct a large space system using the Space Shuttle orbiter—whereas, the SOC is projected as a permanentaly manned facility operating in low-earth orbit and used for operational support of space activities; construction and checkout of large space systems; unmanned and manned orbital transfer vehicle operations; and on-orbit assembly, launch, recovery, and servicing of space vehicles. Resupply is planned via Space Shuttle, and modules are to be transported to and from low-earth orbit (internal to the Space Shuttle). If specific elements are not transportable by the Shuttle, they shall be constructed on orbit as contemplated for the SPS precursor. For purposes of establishing an evolutionary scenario applicable to the SPS precursor, it was assumed that the STS orbiter and its support facilities would be available in 1990.

[1] *Space Construction System Analysis* (NAS9-15718), Rockwell International, SSD 80-0041 (June 1980).

[2] *Requirements for a Space Operations Center*, NASA-JSC-16244 (November 1979).

3.0 SPS DEVELOPMENT SCENARIO

3.1 INTRODUCTION

Fundamentally, a total system proof of concept entails component manufacturing, launch to orbit, space construction, and system operation measurable to a performance specification. More specifically, it must involve validation from orbit of key technology issues. Where deemed necessary, full-scale system elements are to be employed. Funding for the demonstration must meet two basic requirements. First, the overall funding level shall be reasonably low, and achieve results commensurate with the desired goals. Second, funding commitments shall also be conservative during the early time frame of the GBED programs, and still be compatible with the program schedule.

Two planning scenarios are postulated to encompass a full spectrum of required sequences associated with the two families of SPS satellite concepts studied (Figure 3.1-1). The first is a planar concept and the other is a satellite with primary and secondary reflectors utilizing a sandwich solar cell/solid-state electronics assembly at the antenna. The concepts defined during the study are summarized in Section 4.1.

Each precursor satellite, individually directed at one of the "family" of configurations, was studied during this contract period and represents the basis of programmatic scenarios developed. Characteristics of the three-trough concepts vary as to the method of microwave power generation—klystron tube, magnetron tube, and solid-state electronics. The final precursor design is expected to be as prototypical of these concepts (or that of the ultimately preferred SPS design) as to validate necessary ground test simulations and projected space operational requirements.

3.2 SPS PILOT PLANT—PLANAR CONCEPT

Completion of the SPS Technology Advancement phase of SPS research and development by 1987 will provide the technical confidence to proceed with the full-scale precursor development and demonstration phase. The primary objective of this development is to confirm the proof of concept and to demonstrate commercial viability of the SPS to sponsoring agencies, utility firms and consortiums, along with other interested groups that would ultimately interact with the production system and benefit from its capabilities. The proposed precursor demonstration program, as shown in Figure 3.2-1, reflects in general the concept and phasing of this activity for cost-effective results and early design implementation.

The precursor satellite would be constructed in LEO by using the Space Shuttle system for mass transfer and construction support. The construction of an antenna frame, initially to serve as a demonstration article, is contemplated as the first step. LEO base facilities will be subsequently expanded

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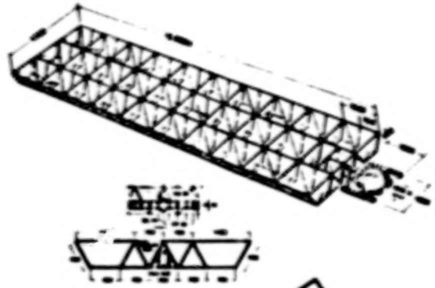
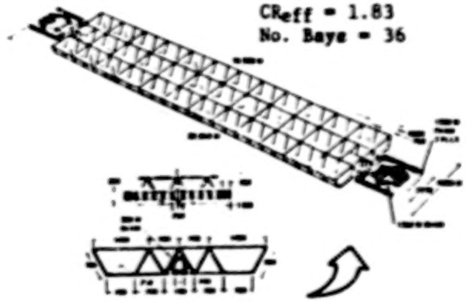
CR_{eff} = 1.83
No. Bays = 30
Mass = 31.63×10⁶ kg
Power at Utility I/F = 5.00 GW
Specific Mass = 6.33 kg/kW

SPS CR-2 REFERENCE CONFIGURATION (3-TROUGH/PLANAR/KLYSTRON)



CR_{eff} = 1.83
No. Bays - 30
Mass = 26.7×10^{6} kg
Power at Utility I/F = 5.6 GW
Specific Mass = 4.77 kg/kW

SPS CR-2 MAGNETRON CONFIGURATION (3-TROUGH/PLANAR)



CR_{eff} = 1.83
No. Bays = 36

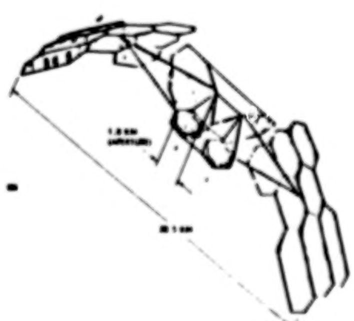
No. Panels = 72
Solar Array Power Generated = 11.46 GW
Power at Utility = 5.22 GW
Sp. Mass = 7.66 kg/kW_{util}

SPS CR-2 SOLID-STATE CONFIGURATION (3-TROUGH/PLANAR/DUAL END-MOUNTED ANTENNA)

GaAs Solar Panels
Effective CR = 5.2

Specific Mass = 8.48 kg/kW Util. I/F

Power at Utility Interface = 1.21 GW per antenna (2.42 GW total)
Mass with Growth (dry) = 20.53×10^{6} kg

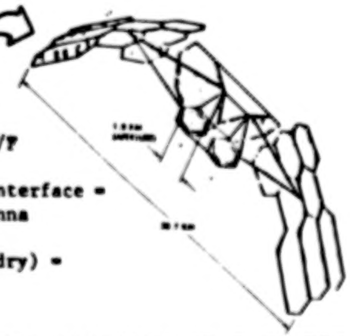


SOLID-STATE GaAs SANDWICH CR-5 CONFIGURATION (DUAL REFLECTORS/ANTENNAS)

MBG Solar Panels
Effective CR = 5.2

Specific Mass = 5.35 kg/kW Util. I/F

Power at Utility Interface = 1.53 GW per antenna (3.06 GW total)
Mass with Growth (dry) = 16.39×10^{6} kg



SOLID-STATE GaAlAs MBG SANDWICH CR-5 CONFIGURATION (DUAL REFLECTORS/ANTENNAS)

Figure 3.1-1. Rockwell SPS Concepts—1980

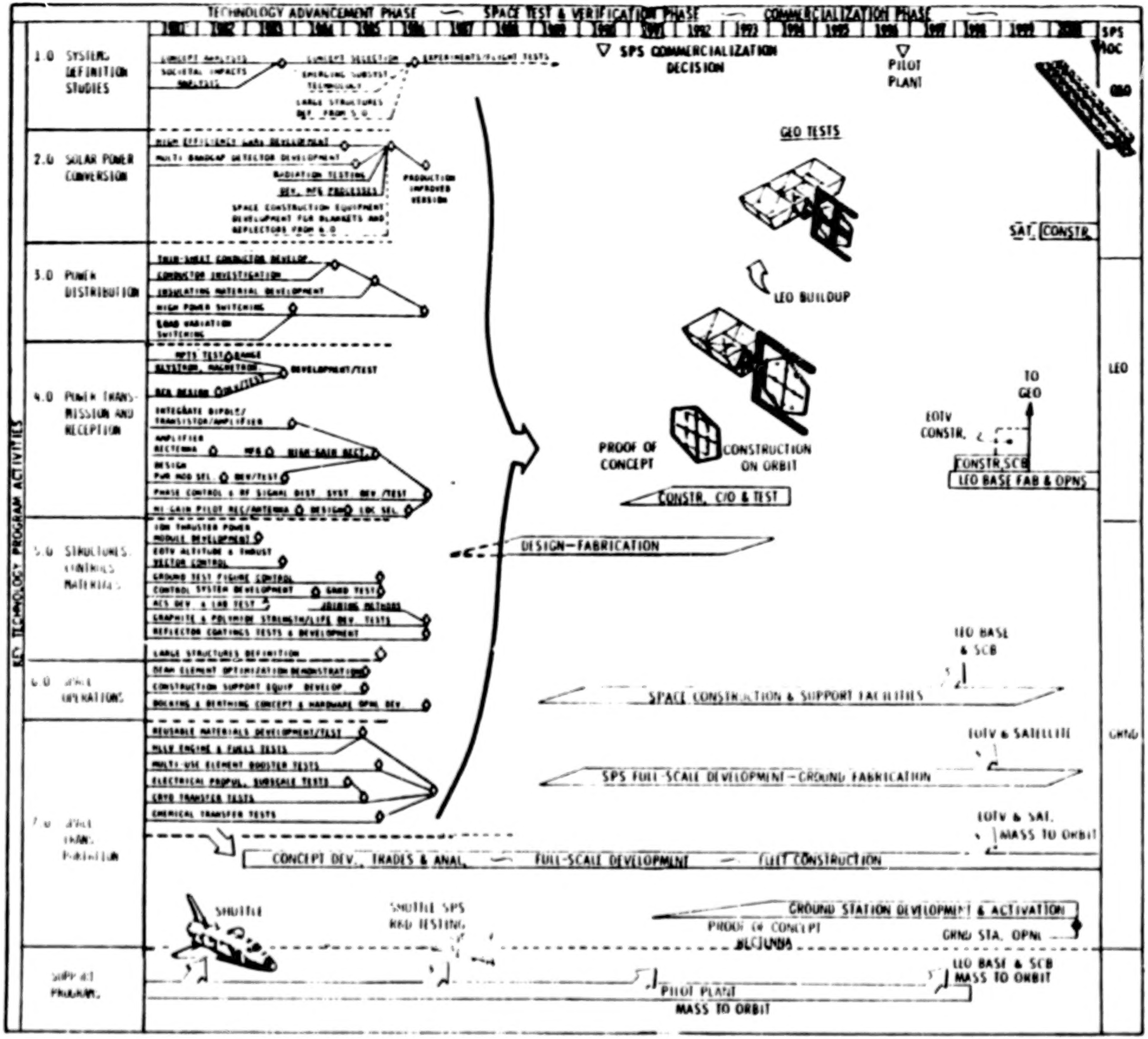


Figure 3.2-1. SPS Scenario—Planar Concept

to accommodate the pilot plant buildup and fabrication of a single solar panel bay equivalent in design to that contemplated for the satellite. A yoke is fabricated at the solar bay and serves as a mounting for the antenna frame. Subsequent assembly of antenna subarrays, solar panels, power distribution and conditioning, and remaining subsystems will prepare the article for orbital checkout and initial test. The pilot plant can be expanded by the addition of solar panel bays, and antenna subarrays as may be required for further LEO testing or as considered necessary for GEO test verification and operations checkout.

An evolutionary construction scenario is illustrated in Figure 3.2-2 to describe the concept of a basic construction facility fabricated in LEO and utilized in low orbit to build the bay and antenna yoke. This design has an integral bay with the capability of transferring the pilot plant to GEO and to provide power for tests. A primary consideration of this development is the utilization of that "bay" as the power module. (This scenario allows common development and the verification of a construction facility that could be expanded into an SPS assembly fixture.) As the antenna frame is being fabricated, Shuttle external tanks are delivered and mated to form a construction fixture for use in fabricating the EOTV bay and antenna yoke.

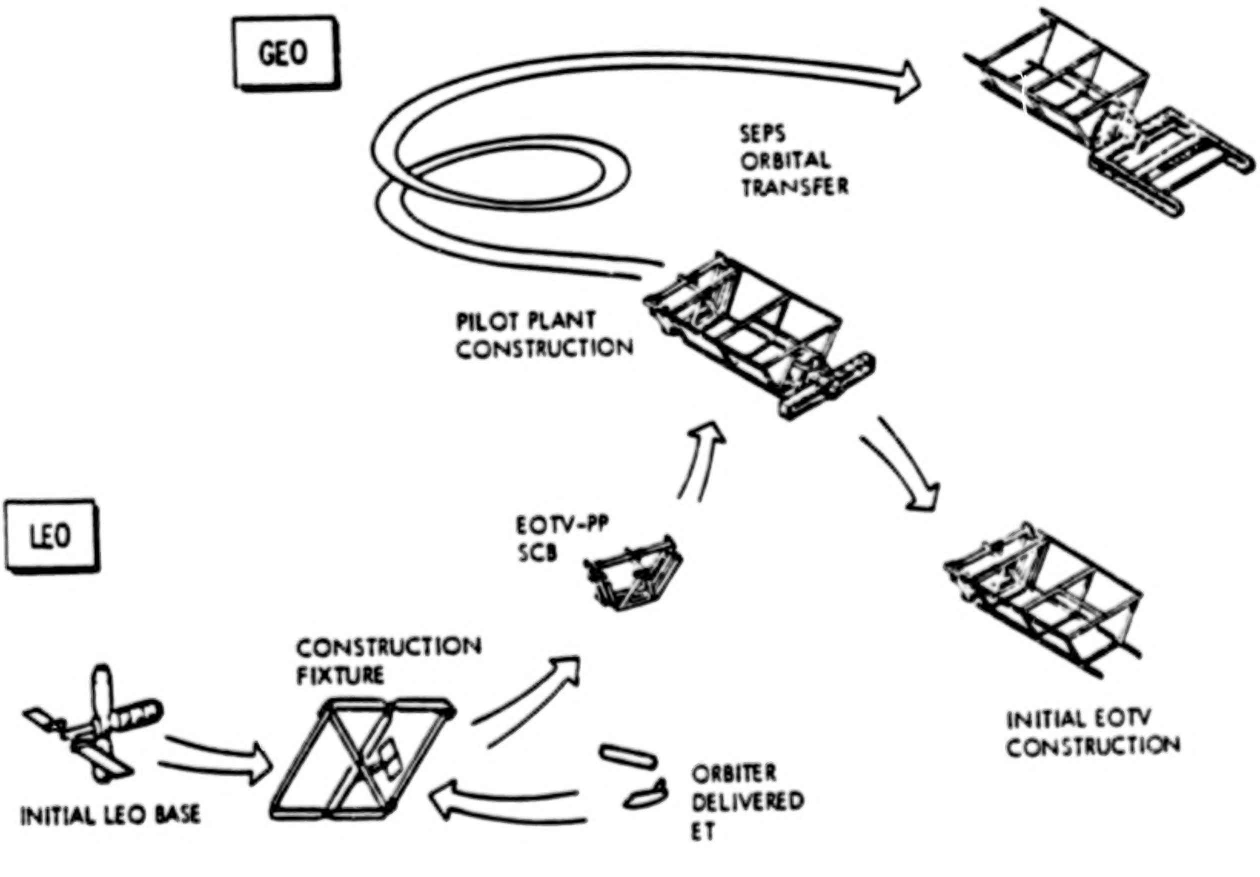


Figure 3.2-2. EOTV Pilot Plant Construction Scenario

3.3 SPS PILOT PLANT—SANDWICH PANEL CONCEPT

During the past several years, Rockwell has placed considerable emphasis on the optimization of SPS concepts and on the development of new concepts stemming from lessons learned and from further in-depth studies of subsystems and advancing technology. One such concept is represented by the second "family" of satellite configurations, where the basic design approach is the integration of solar panels and the microwave generation and transmission system.

This sandwich panel concept employs "layers" of needed elements sandwiched together and constructed in specified modular areas, or panels. One outer layer is the solar cell blanket and the other outer layer the RF transmitting elements, i.e., dipoles. The in-between layers contain the power distribution and phase control wiring, and the power amplifiers. This assembly is described in Rockwell technical papers as a *solid-state sandwich panel*, and satellite configurations have been developed using this approach. For the operational configuration, additional reflector area is added to increase the illumination on the solar cells. The demonstration system (antenna frame) and the pilot plant are discussed herein.

A proposed scenario for the solid-state panel satellite is shown in Figure 3.3-1. It illustrates a synthesized program reflecting recommendations for (1) a projected six-year plan of ground-based exploratory development within the technology advancement phase, (2) the satellite proof-of-concept developments/demonstrations, and (3) the SPS commercialization phase leading to a full-up operational capability in the year 2000.

3.4 ANTENNA FRAME DEMONSTRATION AND TEST ARTICLE (TOTAL PROOF OF CONCEPT)

A first step toward the completion of an SPS pilot plant, as illustrated in the proposed scenario, is the construction of an antenna frame to serve as a test bed and main element of the ultimate proof-of-concept test vehicle. This scenario is principally applicable to any SPS concept and, although a significant effort, the implementation of this program can be carried out by the use of an appropriately equipped space operations center or Space Shuttle orbiter. Development stages of a beam-machine-generated test article[1] is illustrated in Figure 3.4-1, although further study is needed to consider other construction approaches.

In this illustration, development steps lead to the fabrication of a scale model and ultimately a full-scale tri-beam constructed hexagonal frame. Installation and checkout of control systems, microwave generators, and test article subsystems will prepare the antenna frame for test and verification in the early 1990's, or before.

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[1] *SPS-LSST Systems Analysis and Integration Test for SPS Flight Test Article*, NASA/MSFC Contract NAS8-32475, Exhibit E, Space Operations and Satellite Systems Division, Rockwell International, SSD 80-0102 (August 1980).

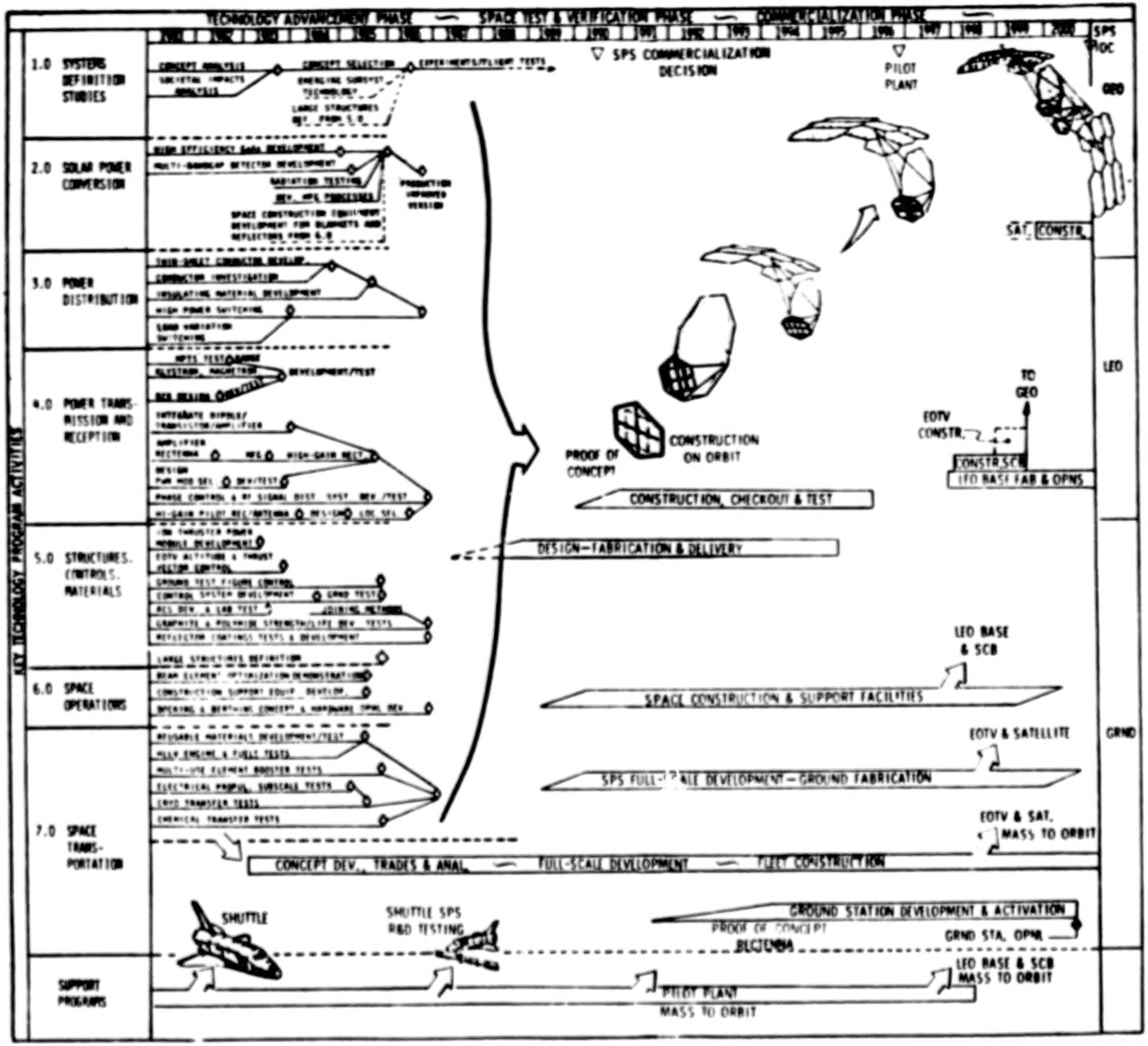

Figure 3.3-1. SPS Scenario—Solid-State Panel Satellite

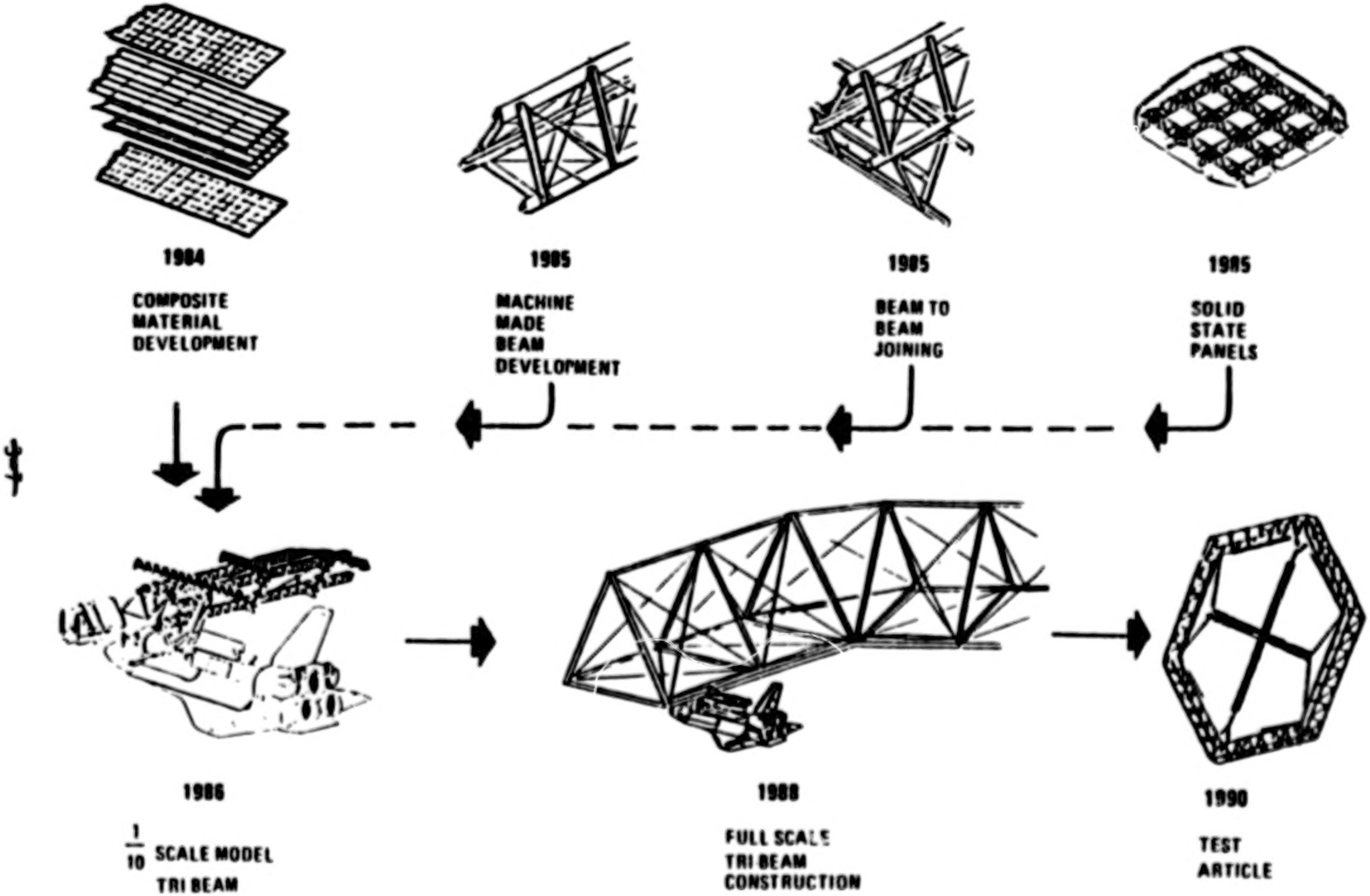

Figure 3.4-1. SPS Test Article I Development Stages (Example Structure)

The antenna frame test will make maximum use of anticipted GBED program results, involve ground support systems, provide RF transmission/reception verifications of efficiency-phase control-beam shaping, identify environmental interactions, establish subsystem performances, and demonstrate space construction techniques. Figure 3.4-2 illustrates a projected mission plan and test sequences of the demonstration/test article. These experiments/tests also integrate the needs of more than one technical area and represent confirmations of ground-based activities which, because of their size or difficulty in duplicating environmental conditions, could not be verified on the ground.

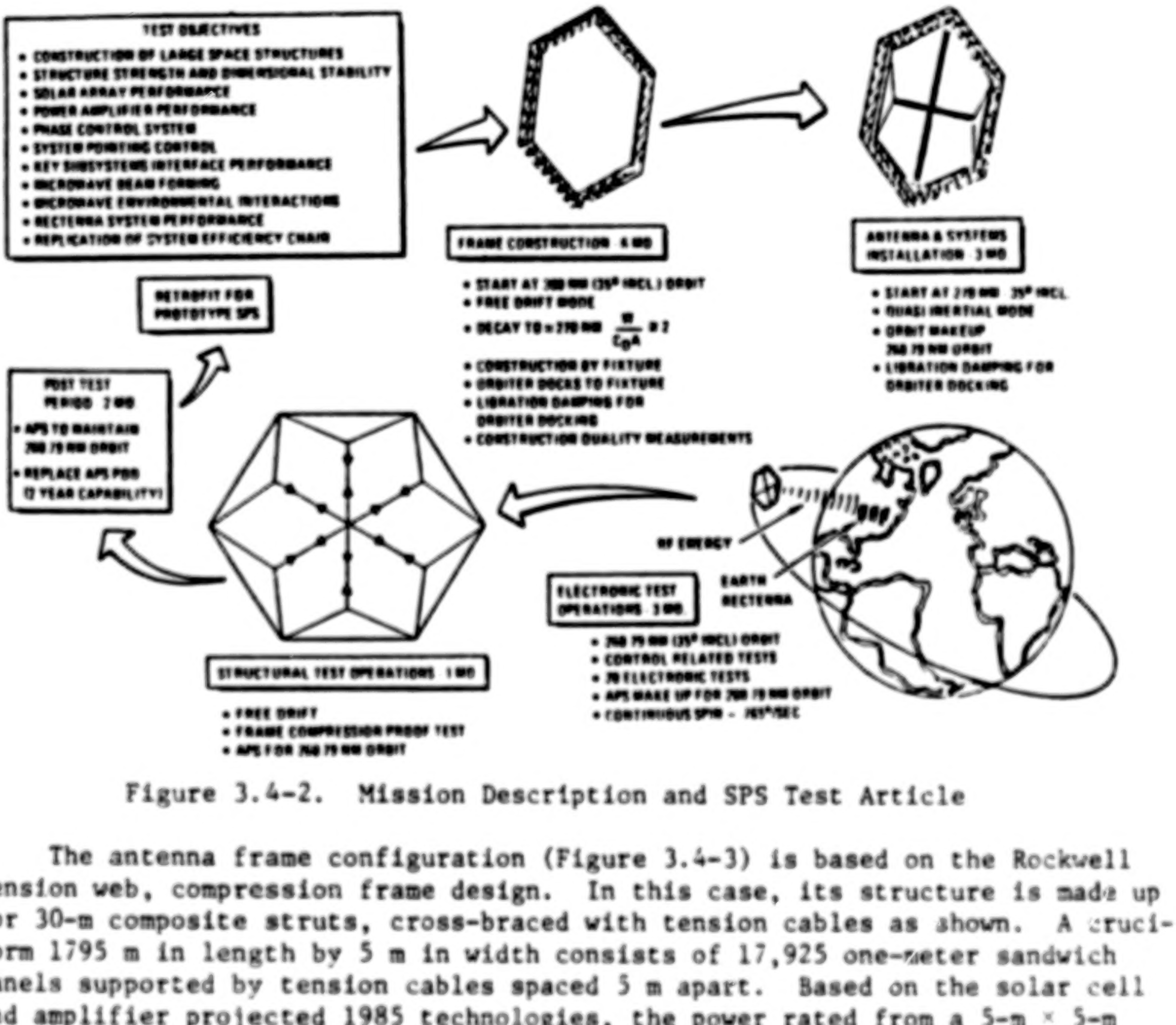

Figure 3.4-2. Mission Description and SPS Test Article

The antenna frame configuration (Figure 3.4-3) is based on the Rockwell tension web, compression frame design. In this case, its structure is made up for 30-m composite struts, cross-braced with tension cables as shown. A cruciform 1795 m in length by 5 m in width consists of 17,925 one-meter sandwich panels supported by tension cables spaced 5 m apart. Based on the solar cell and amplifier projected 1985 technologies, the power rated from a 5-m × 5-m panel group is estimated to be 125 W/m^2. Four 5-m × 5-m panel groups comprise a basic RF phase controlled module. There are, therefore 717 active phase controlled RF modules in the satellite.

The desire to configure the demonstration concept on the basis of a full-scale MW antenna design involved a review of structural approaches which could be achieved within the timeframe under consideration, and would be compatible with the Space Shuttle's payload capabilities. Three candidate structure concepts are depicted in Figure 3.4-4 using two fundamentally different approaches.

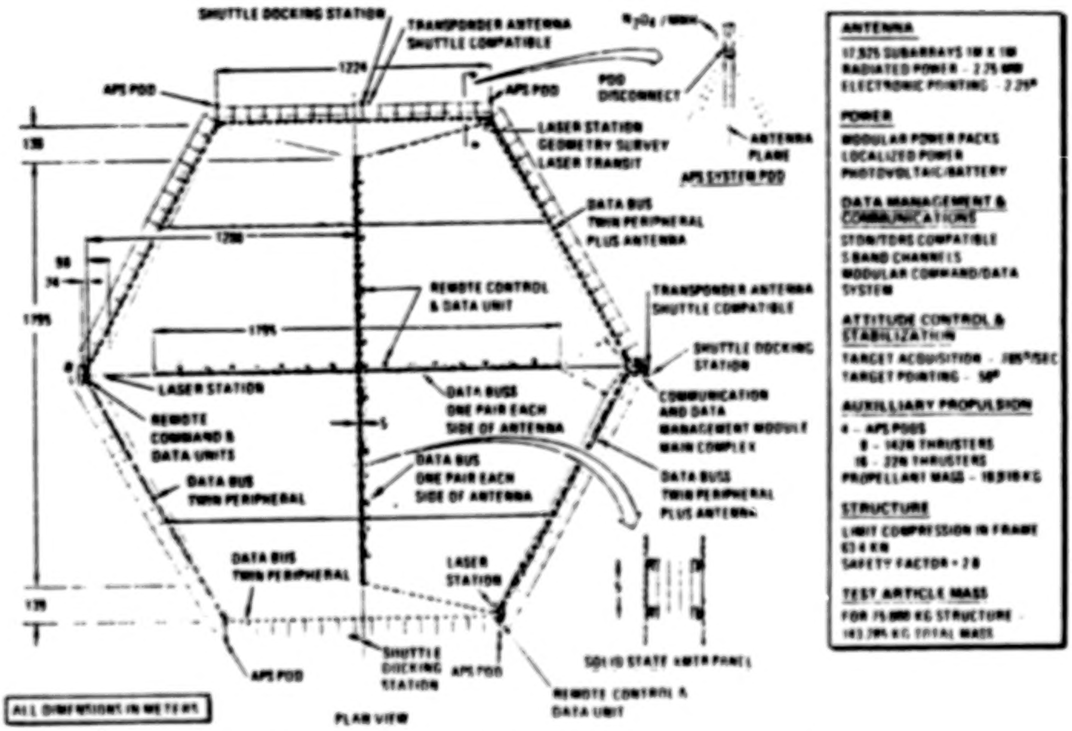

Figure 3.4-3. Demonstration/Test Article Configuration

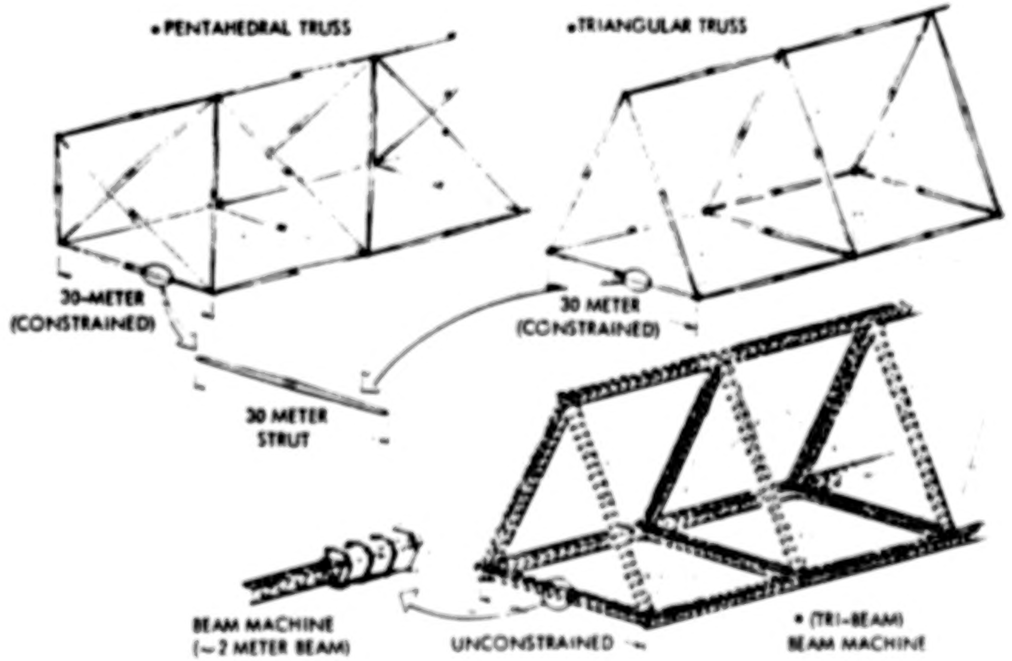

Figure 3.4-4. Candidate Antenna Structural Concepts

The first approach uses a 30-m hinged, nestable tapered strut (Figure 3.4-5) which is built up of graphite-epoxy composites. A ball-socket swivel joint concept for easy joining of these struts is shown in Figure 3.4-6. When

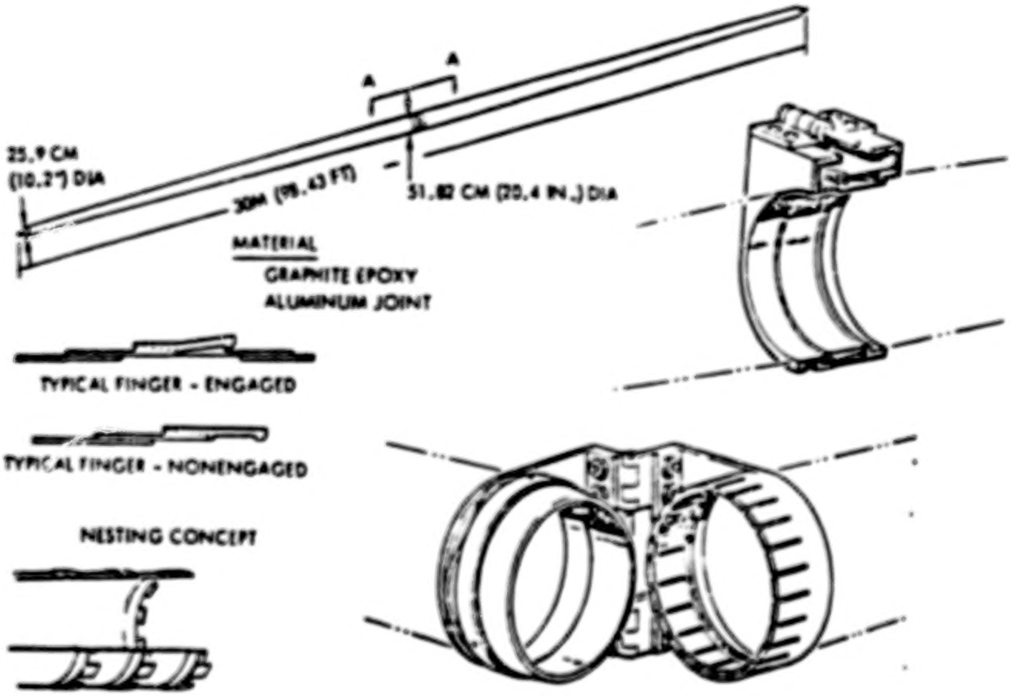

Figure 3.4-5. Hinged Nestable Tapered Strut

Figure 3.4-6. Ball-Socket Swivel Joint Concept

folded and nested (e.g., like dixie cups), the struts can be stowed within the cargo bay of the Space Shuttle orbiter. Either of the two beam configurations —pentahedral truss or triangular truss—could be employed.

Alternatively, an automated beam machine could be used, such as currently under development by the NASA. Both approaches were compared on a mass versus center deflection basis. The data generated (Figure 3.4-7) were based on a fully populated MW antenna located at GEO in order to design growth capability into the demonstration concept. Previous analyses have indicated an allowable maximum center deflection of from 16 to 24 cm is acceptable and, although the beam machine approach is projected to be clearly superior, it was decided that the more conservative strut/joint concept should be used until the beam machine is developed further. Of these three concepts, therefore, the triangular truss using 30-m struts was selected.

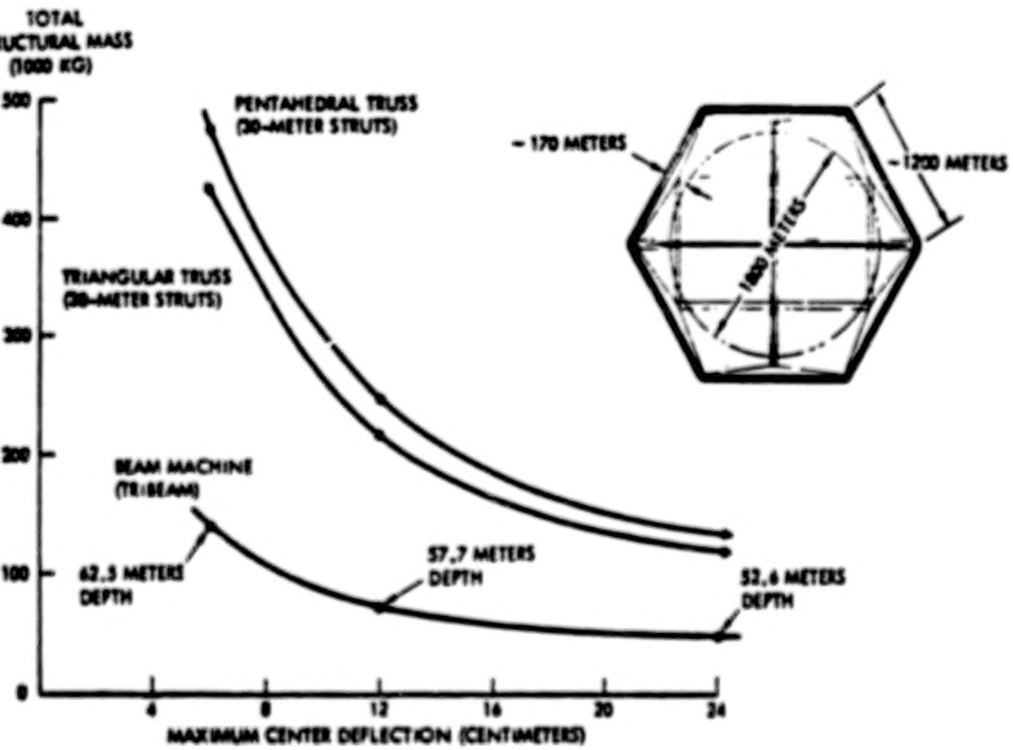

Figure 3.4-7. Candidate Structural Concept Trades

3.5 ORBITAL ASSEMBLY

Assembly of the satellite structure on orbit was investigated and it was determined that some type of assembly jig would be required. Concepts were developed and an example structure jig for the triangular truss is illustrated in Figure 3.5-1. A docking adapter is stationed at one side of the jig to accommodate the Space Shuttle orbiter as it brings up the required payloads. As envisioned, the structural jig would be completely automated since the processes for satellite assembly are simple and highly repetitious. Assembly of the satellite structure, strut by strut, is accomplished within the jig

framework shown. Basically, the jig consists of deployable Astromasts and hinged struts. Figure 3.5-2 depicts a concept for packaging and deploying the assembly jig.

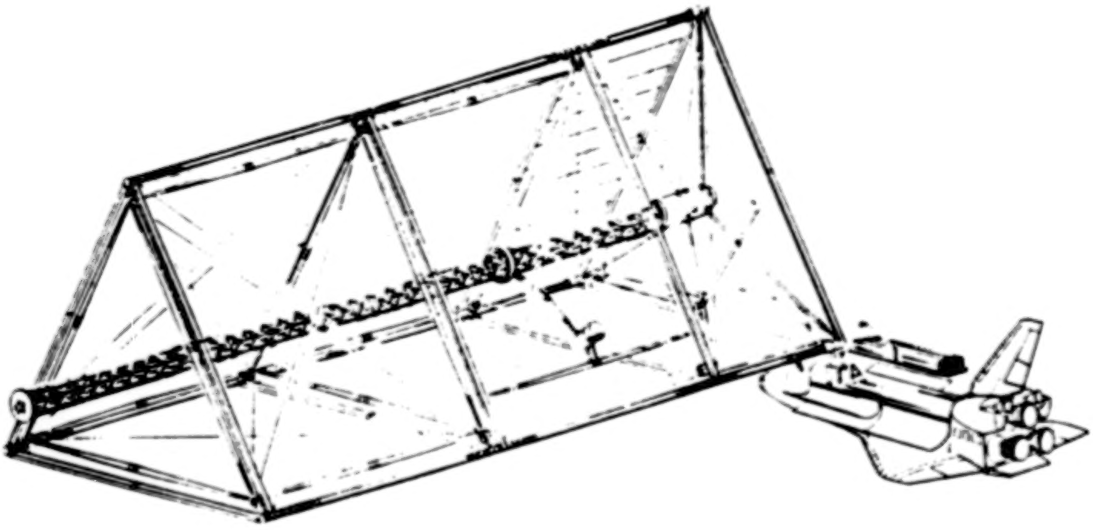

Figure 3.5-1. Structural Jig Concept for Triangular Truss

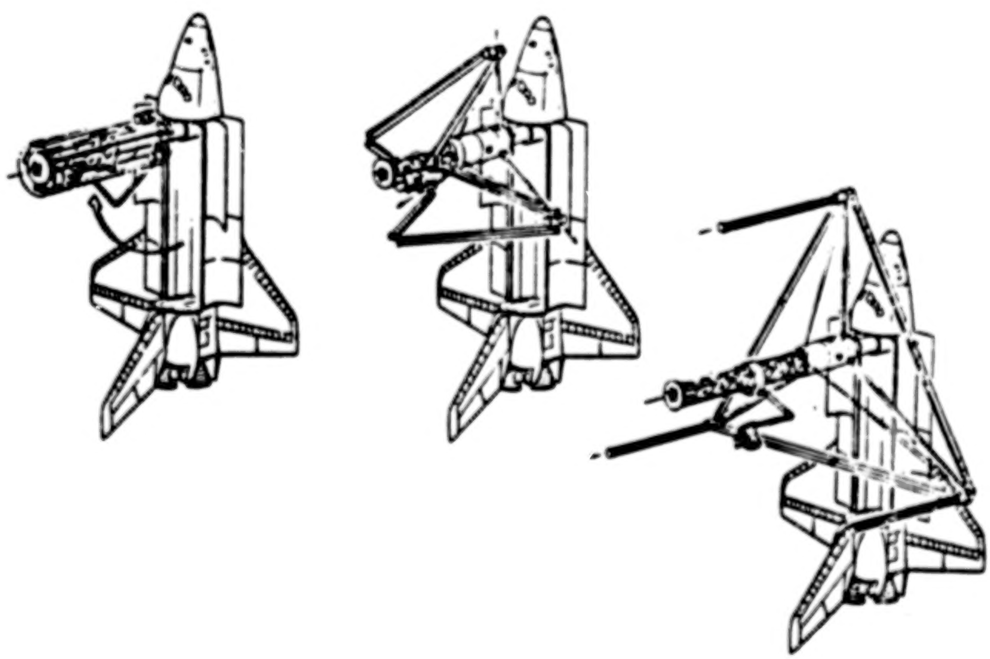

Figure 3.5-2. Concept for Antenna Structural Jig Deployment

As each 30-m length of triangular truss is completed, it is "extruded" from the structural jig. This deployment scheme for the structure and the cable network is illustrated in Figure 3.5-3. The cables constrain motion within the "web" plane of the satellite. (It is anticipated that some form

of active control may be required to ensure stability out of this plane.) The cables which constitute the cruciform are assumed to be doubled over pulleys so that the 5×5-m RF panels can be "clotheslined" across from one end. This concept needs in-depth study to ensure that all assembly functions can be conducted in a safe, viable manner.

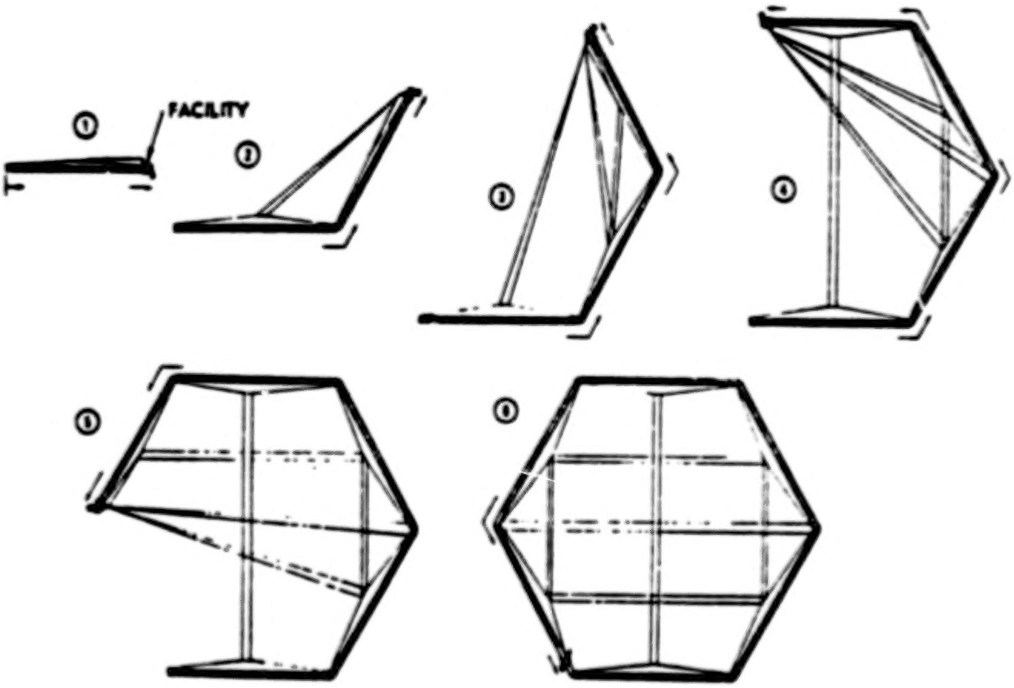

Figure 3.5-3. Cable Network Deployment

The ideal orbital position for antenna frame demonstration purposes would be to have the LEO satellite directly over the rectenna site at noon, since this most closely approximates the operational system at GEO. Figure 3.5-4 illustrates that under these orbital conditions, a full two minutes of power transmission and phase control testing can be conducted at the attitudes and

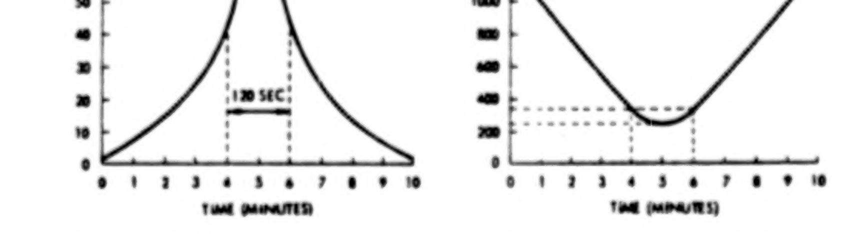

Figure 3.5-4. Flight Data Relative to Ground Site

inclinations noted. These data are based upon operating the satellite and + and - 45° from its zenith point; and, as indicated by the data, the time could be increased by expanding the view (elevation) angles. Due to orbital regression, it is estimated that measurements could be taken over a single fixed site 9 days out of 48. To supplement these opportunities, provisions have been made (e.g., added mass and costs) to include batteries on board the satellite, thereby allowing daily testing to be conducted. Variations in received power levels will be experienced as functions of elevation angles, slant range, and sun angles; however, since the exact positions of those will be known, actual measurements can be correlated with the calculated performance specifications.

3.6 PILOT PLANT TEST VERIFICATION

At this point in the verification process, experiments and pilot plant tests are primarily concerned with identifiable unknowns such as thermal effects on tolerance, plasma effects on orbit, etc.; however, the experience of building the structure will in itself identify limitations in techniques and serve to define the procedures, configurations, hardware, and material which can best serve an operational SPS. Table 3.6-1 summarizes a number of tests applicable at various steps of pilot plant development, as shown in Figures 3.2-1 and 3.3-1.

A direct fallout of employing key full-scale elements in the precursor proof-of-concept program is that given an SPS program commitment; the demonstration system can be incrementally upgraded to operate as a pilot plant at geosynchronous orbit in the first half of the 1990 decade.

3.7 RECTENNA DESIGN CONCEPT

A major advantage of transmission across the larger aperture MW transmitting antenna is realized in the small size of the receiving antenna (i.e., the rectenna). Figure 3.7-1 illustrates the resulting rectenna size requirement which is approximately one-half the area of a football field. The rectenna panels are comprised of dipoles, appropriately spaced, on a ground plane of wire mesh builders "cloth." If desired, the rectenna could be built for transportability and demonstrated at sites throughout the U.S. As shown in the lower center of the figure, the calculated maximum incident radiation level is low and unquestionably safe—yet, MW energy capture over the 2500 m^2 will develop a maximum power level of 18.75 kW.

3.8 COSTS AND CONCLUSIONS

The basic recommendations is that Phase A studies should be initiated as soon as possible. The objective of these studies would be to develop the current ground-based exploratory developments and other demonstration concepts to the depth necessary for a comparison and evaluation of alternative concepts and configurations, responsive to SPS requirement defintions of power conversion, microwave systems, construction approaches, transportation technologies, electric power distribution, structures/controls/materials, and testing operations. The evaluation of these alternative approaches would be based upon cost-effectiveness and schedule compatibility within the domains of achievable

Table 3.6-1. Tentative List of Experiment/Flight Tests for Pilot Plant

	AREAS OF EXPLORATORY RESEARCH AND DEVELOPMENT						
	1.0 SYSTEMS ANAL. & TECHNOLOGY	2.0 SOLAR POWER CONVERSION	3.0 POWER DISTRIBUTION	4.0 PWR TRANSMISSION & RECEPTION	5.0 STRUCT., CONTROLS & MATER'LS	6.0 SPACE OPERATIONS	7.0 TRANSPORTATION
HIGH-VOLTAGE PLASMA INTERACTION	(2)(3) SPS CONCEPT DEFINITION	(2) PLASMA LEAKAGE FROM SOLAR ARRAYS, LEO (3) PLASMA LEAKAGE FROM SOLAR ARRAYS (GEO)	(2)(3) POWER BUS LEAKAGE TO PLASMA ENVIR. & ARCING BETWEEN BUSES	(2)(3) HIGH-VOLTAGE PLASMA EFFECTS ON KLYSTRONS AND MAGNETRONS	(2)(3) INSULATION DEVELOPMENT	CONSTRUCTION UNDER PLASMA CONDITIONS	
TOLERANCE BUILDUP DURING CONSTRUCTION & OPERATIONS	(1)(2)(3) COMPREHENSION OF SUBSYSTEM INTERACTIONS	(2)(3) THERMAL DISTRIBUTION	(2)(3) THERMAL DISTRIBUTION	(2)(3) THERMAL DISTRIBUTION	(1)(2)(3) STRUCTURE EFFECTS CONTROL REQMTS ON LARGE STRUCTURE FIGURES	(1)(2)(3) CONSTRUCTION EQUIPMENT	(1)(2)(3) COMPONENT DELIVERY
THERMAL DISTORTION CONTROL—CRITICAL ELEMENT	"	(2)(3) CONSTRUCTION FLATNESS	(2)(3) ROTARY JOINT	(2)(3) WAVEGUIDE TOLERANCE, FLATNESS, PHASE CONTROL SYSTEM			
HEAT REJECTION OF MICROWAVE GENERATORS	"	(2)(3) MUST BE OPERATING DURING EXPERIMENT	(2)(3) MUST BE OPERATING DURING EXPERIMENT	(2)(3) INVESTIGATION OF ANT. TAPER, PHASE CONTROL, RECTENNA SIZING	MATERIALS SELECTION, CONTROLS STRUCTURAL INSTALLATION	INSTALLATION PROCEDURES	
WAVEGUIDE TEMPERATURE CONTROL	"	"	"	(2)(3) EMITTING WAVEGUIDES HAVE PRECISION TOLERANCES	"	"	
ELECTROSTATIC CHARGING	"	(2)(3) CHARGING & DISCHARGING OF MATERIALS SUCH AS REFLECTORS	(2)(3) CHARGING INVESTIGATIONS	(2)(3) CHARGING INVESTIGATIONS	"	"	
PHASE CONTROL AND ANTENNA POINTING	(1)(2)(3) CONCEPT DEFINITION "	(2)(3) MUST BE OPERATING DURING EXPERIMENT	(2)(3) MUST BE OPERATING DURING EXPERIMENT	(2)(3) PILOT ANTENNA ENVIRONMENTAL EFFECTS, ACCURACY, COMPONENT CHECKOUT	(1)(2)(3) FIGURE CONTROL		

LEGEND: (1) Antenna frame
(2) Pilot plant at LEO
(3) Pilot plan at GEO

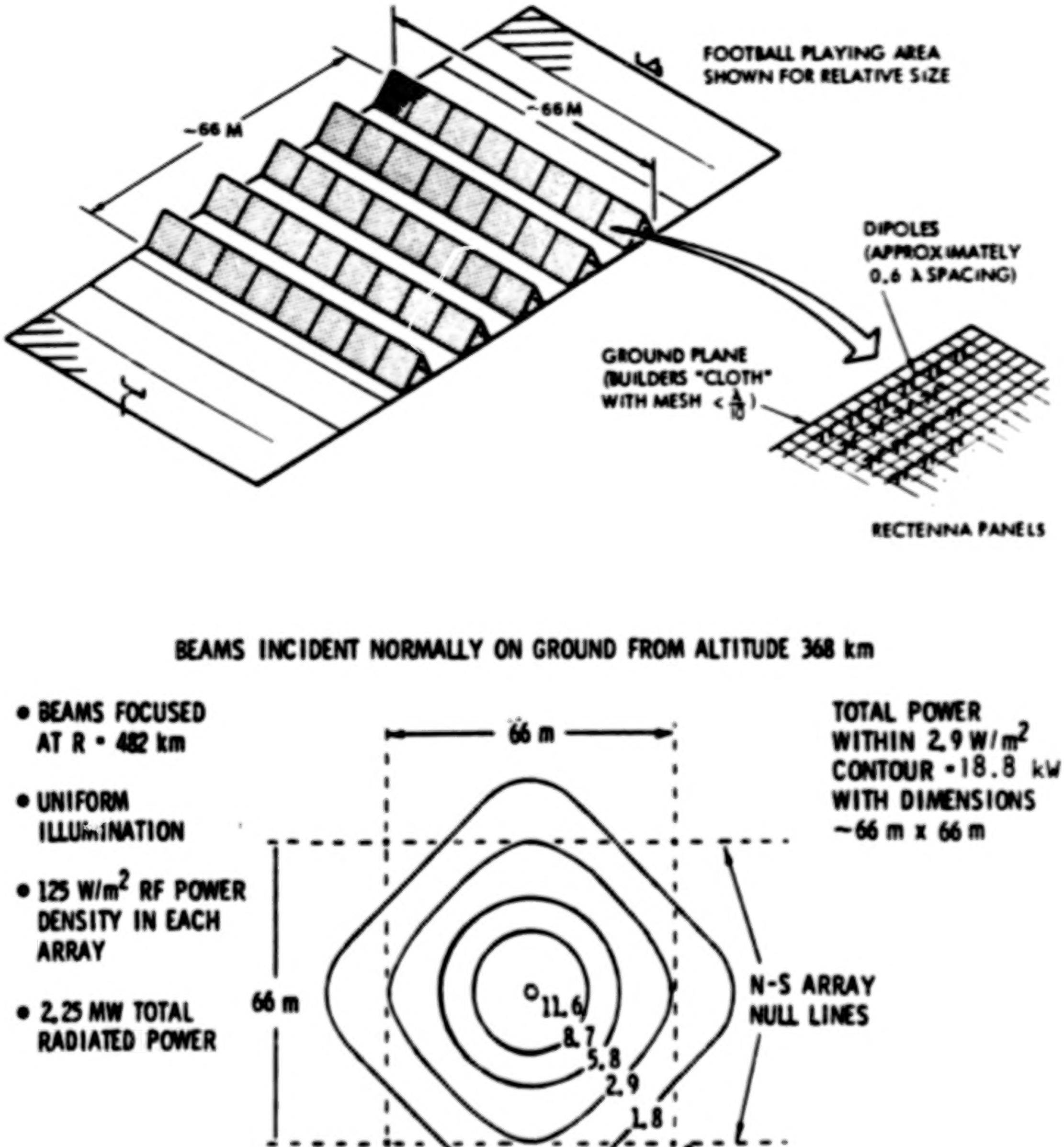

Figure 3.7-1. Rectenna Considerations

technology and decision-making requirements. The anticipated positive results of these studies should significantly enhance the technical feasibility of SPS as an economically viable source of base load power for the near future.

The recent Rockwell study efforts, conducted within the bounds of SPS demonstration objectives, guidelines, constraints, and requirements yielded a number of significant findings:

- A total proof-of-concept demonstration can be developed and tested in the early 1990's based on a ground-based exploratory program of the 1980's.

- The system concept can be demonstrated with a precursor satellite at low earth orbit.

- The R&D and precursor demonstration project are designed to provide the system technology base operations and hardware needed for SPS program confirmation.

- Projected technology advancements from on-going DOE and NASA programs and recommended R&D activity are considered adequate for the demonstration concept.

- Power collection can be demonstrated by a transportable rectenna farm of approximately one-half an acre (approximately one-half the playing area of a football field).

- The precursor concepts are planned to duplicate and validate key interfaces of the operational SPS efficiency chain and concept definition.

- The demonstration concept has been designed for ultimate growth into an operational GEO pilot plant in the mid-1990's.

Elements of the antenna frame demonstration program are shown in Figure 3.8-1, starting with the Space Shuttles for earth launch and ending with production facilities (pilot scale) for manufacturing the required demonstration hardware. For the concept chosen, it is worthwhile to note that the technology driver—from a schedule standpoint—is expected to be the sandwich panel, comprised of thin-film GaAs cells and solid-state MW amplifiers. Combining the two into a panel is not anticipated to be difficult and the development of each technology is covered by the R&D plan.

Schedule compatibility with the R&D program is reflected by the annual funding curve shown in Figure 3.8-2, wherein substantial costs are not incurred until after a successful R&D program has been accomplished.

• LAUNCH SYSTEMS		• SPACE SHUTTLES
• SPACE SUPPORT SYSTEMS		• STRUCTURAL JIG • DOCKING MODULE
• SATELLITE SYSTEMS	• SANDWICH PANEL	• SOLAR CELLS • BATTERIES • PC&C • CONJUGATING ELECTRONICS • PHASE CONTROL DISTRIB. • SOLID-STATE AMPS • STRUCTURE • ANTENNA ELEMENTS
	• PHASE CONTROL	• WIRING • TRANSMITTER • OSCILLATOR
	• STRUCTURE	• STRUTS • CROSS-BRACE CABLES • JOINTS • CATENARIES • SP SUPPORT CABLES
	• ACS	• ENGINES • TANKS AND LINES • CONTROLS
	• TT&C	• SENSORS • PROCESSORS • COMMUNICATIONS • WIRING
• GROUND SYSTEMS		• KSC • RECTENNA • TRACKING AND COMMAND STATIONS (EXISTING)
• PRODUCTION FACILITIES		• SANDWICH PANEL • PHASE CONTROL • STRUCTURES • ACS • TT&C

Figure 3.8-1. Elements of the Antenna Frame Demonstration Program

COST OF PROGRAM ELEMENTS/OPERATIONS

• LAUNCH SYSTEMS		$450 M
• SPACE SUPPORT SYSTEMS		$ 40 M
• SATELLITE SYSTEMS	SANDWICH PANEL	$ 80 M
	PHASE CONTROL	$ 10 M
	STRUCTURE	$ 45 M
	ACS/TT&C	$ 20 M
• GROUND SYSTEMS (RECTENNA)		$ 5 M
• PRODUCTION FACILITIES		$ 65 M
		$715 M
• PROGRAM SEM, SUPPORT CONTINGENCY		$ 85 M
		~ $800 M

ANNUAL FUNDING

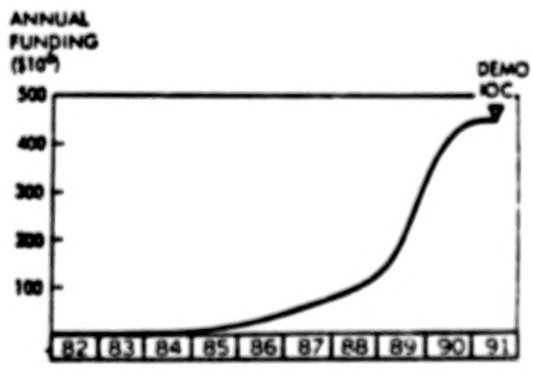

Figure 3.8-2. ROM Proof-Of-Concept Demonstration Program Costs

4.0 SYSTEM SUMMARY

The definition of research and development (R&D) objectives is based upon the identification of technological strength and weaknesses in the necessary satellite, ground station, transportation system/subsystems and in the costs associated with the elements that constitute these subsystems/systems. This section presents, in summary, the various candidate satellite concepts, transportation scenarios, and cost estimates for the Satellite Power System defined during Exhibit D of Contract NAS8-32475. Complete details of the candidate satellites, the transportation system, and system cost factors may be found in Volumes VII, III, and VI, respectively, of the final report (SSD 80-0108) for this study.

4.1 SYSTEM CONCEPTS (AUGUST 1980)

4.1.1 SATELLITE

The present concepts suggested by Rockwell are illustrated in Figures 4.1-1, 4.1-2, and 4.1-3. The first concept (Figure 4.1-1) consists of a three-trough planar solar cell array with a CR_E of 1.83 and utilizes klystrons (or magnetrons) for powering the microwave power transmission array. The klystron variation is essentially an updated version of the end-mounted concept depicted in March 1979.

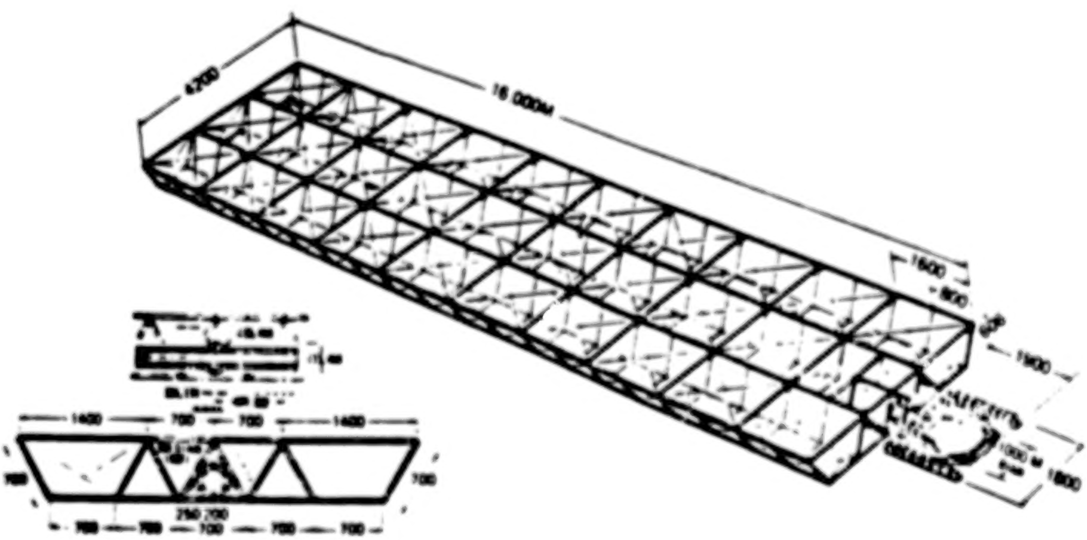

Figure 4.1-1. SPS Reference Configuration, Single End-Mounted Tension Web Antenna—Klystron

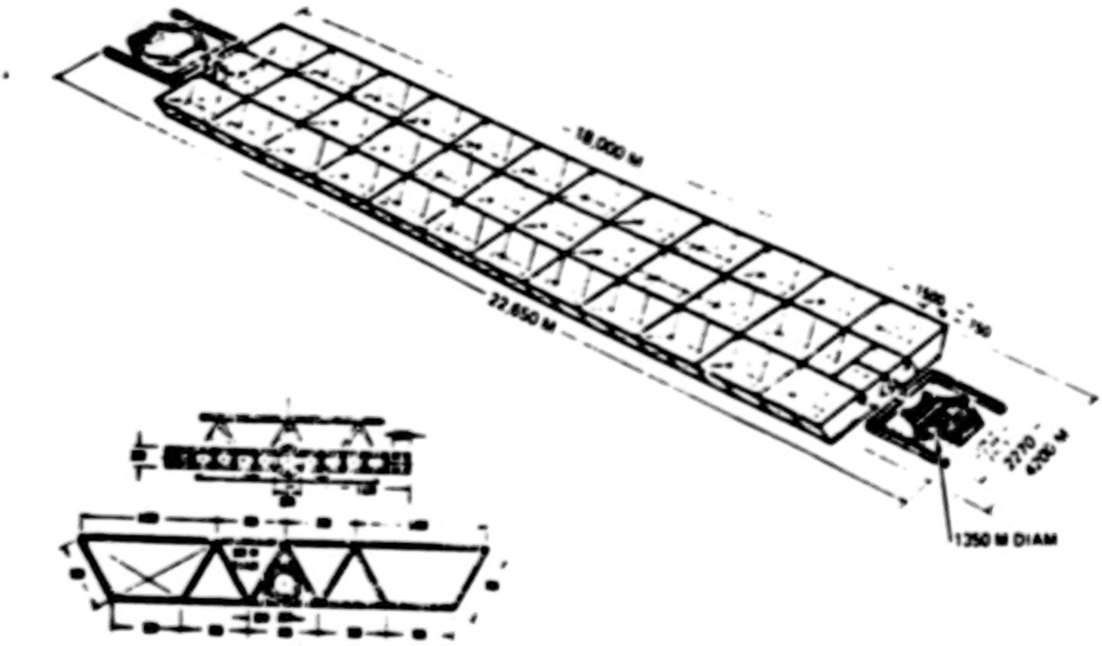

Figure 4.1-2. SPS Solid-State Configuration—
Dual End-Mounted Antenna

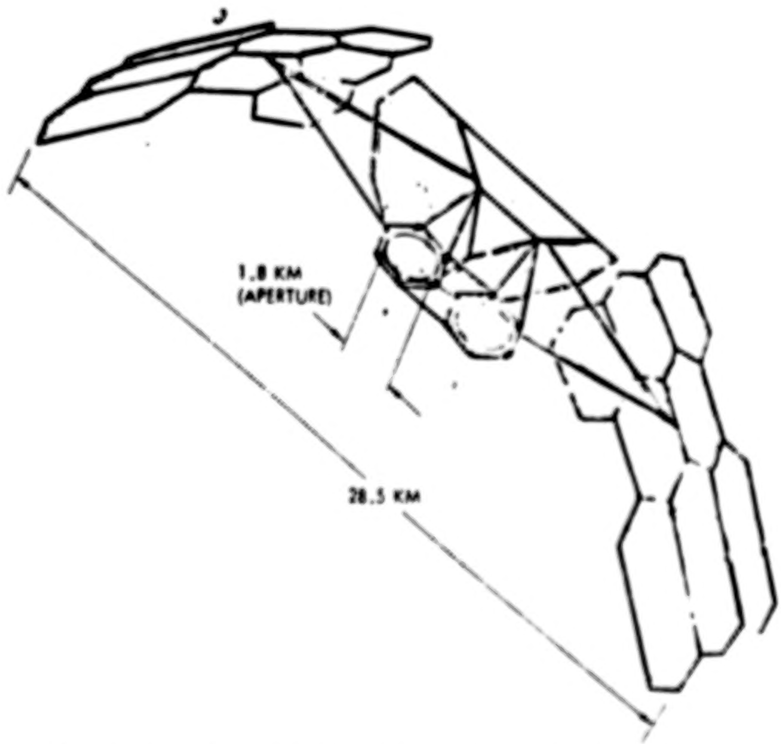

Figure 4.1-3. Solid-State Sandwich Satellite
Point Design Concept

Figures 4.1-2 and 4.1-3 depict the Rockwell alternate concepts that are predicated on the use of advanced technology, solid-state microwave power amplifiers as the means of generating the microwave transmission power beam. The concept in Figure 4.1-2 illustrates a concept similar to the baseline (klystron) reference concept. The solar array in this case remains a three-trough, planar configuration with a CR_E of 1.83. Two antennas are required, one at each end to overcome the lower transmission power (3.68 GW) available at each antenna, and the solar array area is increased to compensate for the lower overall system efficiency. All planar configurations utilize a modified 10-dB Gaussian beam taper to minimize beam side lobe losses.

Figure 4.1-3 represents a major deviation from the planar concepts most often considered for solar photovoltaic power generation satellites. The depicted approach utilizes a CR_E of 5.2 with the solar cell blanket and microwave antenna array forming the outer layer of a "sandwich." The inner layers provide for interconnection and thermal isolation since the desired operating temperature (estimated) for the solar cell and microwave amplifiers are 200°C and 125°C, respectively. The satellite reflector system consists of a large planar mirror that may be adjusted relative to sun, and a relatively flat but adjustable secondary mirror to maintain a focused solar image on the solar blanket.

A major advantage of the "sandwich" configuration is the collocation of the microwave system and the solar power generation elements and, therefore, the elimination of the need for a high-power slip joint. It thus becomes possible to generate voltages directly at levels appropriate to solid-state device operation, eliminating the need for large masses of HV-to-LV dc-dc converters. Full details of each of the candidate concepts are presented in Volume VII of the final report.

4.1.2 GROUND RECEIVING STATION

The various elements of the defined ground receiving station (GRS) are shown in Figure 4.1-4. The major elements of the reference ground receiving station include the basic receiving/rectifying panels (rectenna), the power distribution and power conversion elements, as well as the various supporting elements (maintenance, facilities, land, etc.). The estimated efficiency of the various links of the ground system power chain is shown in Figure 4.1-5. The only factor which is subjected to change are the base dimensions of the rectenna. For example, the rectenna dimensions for the March 1979 system were stated to be 10 km (minor axis) and 13 km (major axis). For the reference system update (klystron) the minor and major axis dimensions remain the same, although the alternate configuration will require smaller rectenna area.

The rectenna panels are located in the center of the receiving station and cover a ground area of approximately 100 km^2 (approximately 25,000 acres). An additional 32 km^2 (approximately 10,000 acres) is required for the distribution and conversion stations plus a security perimeter. Received power is approximately 6.15 GW (at 2.45 GHz). Power available at the utility interface is approximately 5 GW ac.

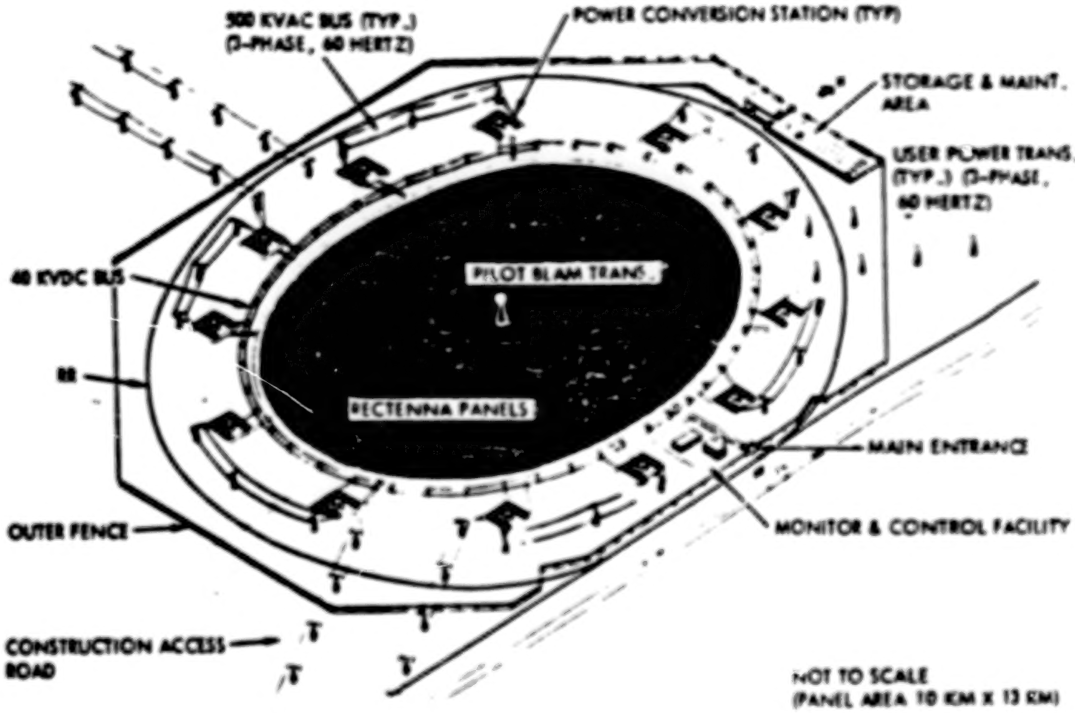

Figure 4.1-4. Ground Receiving Station

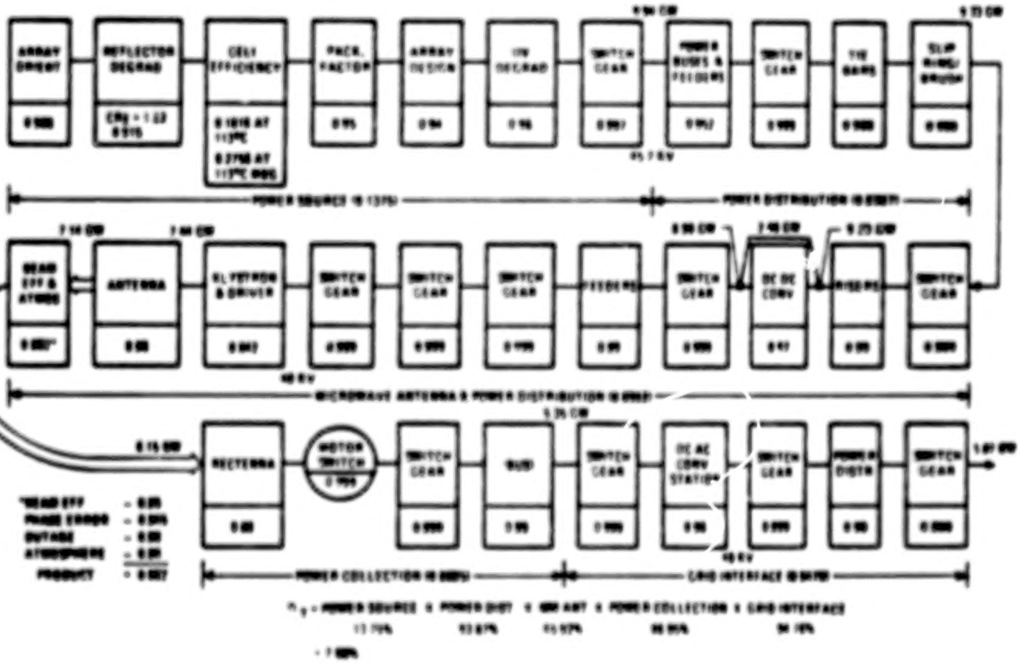

Figure 4.1-5. System Efficiency Chain—Reference Concept (April 1980)

Preliminary analysis of the power beam footpring for the solid-state reference concept, Figure 4.1-2 (two required), and the "sandwich" concept, Figure 4.1-3 (two required), have indicated that the minor axis dimensions are 7.45 km and 4.87 km, respectively (for the single-junction GaAs solar cell configuration). The major axis dimensions are 1.31 times the above figures.

4.2 SUMMARIES

At the present time, seven alternate configurations have been identified in detail. Of these, five have been considered for costing and transportation analysis. The seven configurations are summarized in Table 4.2-1, and consist of the klystron and solid-state antenna configurations utilizing the GaAs and GaAlAs/GaAs solar cells, and a magnetron antenna configuration considering GaAs solar cells only. An eighth alternate magnetron antenna with GaAlAs/GaAs cells has been tentatively defined, but details are not included to any depth in this document.

4.2.1 KLYSTRON MICROWAVE ANTENNA

The recommended satellite concept utilizing a klystron microwave power amplifier is shown in Figure 4.1-1. The illustrated concept consists of an end-mounted microwave power transmission system and a GaAs based three-trough, planar solar array. The array length is 16,000 m for a GaAs single-junction cell, and 11,000 m for an array based upon a GaAlAs/GaAs dual-junction (multi-bandgap) solar cell. The antenna array adds 1900 m to the overall length.

The solar array panels are 730 m long and 650 m wide. Two of these panels make up a voltage string (43.3 kV) when using a single-junction cell. A single panel is capable of providing the necessary 43.3 kV when a multi-bandgap cell is used. The 650 m width consists of 26 strips, each 25 m wide. Sizing of the array is based on a solar constant at summer solstice (1311.5 W/m^2), and an end-of-life concentration ratio of 1.83, an operating temperature of 113°C, and the design factors shown in Figure 4.1-5 (efficiency chain). The installed solar panel area is defined as [illegible] 10^6 m^2 for the standard GaAs cell and 18.47 10^6 m^2 for the MBG cell. Total power from the solar array output is estimated to be 9.94 GW. Total transmitted power is 7.14 GW. System efficiency factors for both satellite configurations are indicated in Figure 4.2-1 (only the cell efficiency differs).

Table 4.2-2 presents a summary of the satellite mass for the two concepts.

4.2.2 END-MOUNTED SOLID-STATE ANTENNA

The satellite concept utilizing end-mounted solid-state antennas is shown in Figure 4.1-2. The basic characteristics are summarized in Table 4.2-3. The illustrated concept consists of a solar array, consisting of either single- or dual-junction solar cells, and dual solid-state microwave power transmitting antenna. In essence, the satellite configuration consists of two end-mounted satellites, each providing one-half the total output, joined together in a back-to-back configuration, sharing a common central crossbeam structure. Overall dimensions of the array are 4200 m wide by 18,000 m long (12,000 m MBG).

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Table 4.2-1. Satellite System Summaries—Alternate Concepts (June 1980)

	GaAs SOLAR CELL				GaAlAs/GaAs SOLAR CELL			
	REFERENCE	DUAL END-MOUNTED	DUAL SANDWICH	MAGNETRON	REFERENCE	DUAL END-MOUNTED	DUAL SANDWICH	MAGNETRON
SATELLITE								
TYPE	PLANAR	PLANAR	COMPOUND	PLANAR	PLANAR	PLANAR	COMPOUND	PLANAR
CR_E	1.83	1.83	5.2	1.83	1.83	1.83	5.2	1.83
DIMENSION (METERS)	4200 × 16,000	4200 × 18,000	6600 × 28,500	4200 × 15,000	4200 × 11,000	4200 × 12,000	TBD	4200 × 10,000
MASS ($\times10^6$ KG)	31.63	39.97	20.53	26.70	25.96	35.57	16.39	21.533
SOLAR ARRAY/ANTENNA	DECOUPLED	DECOUPLED	SANDWICH	DECOUPLED	DECOUPLED	DECOUPLED	SANDWICH	DECOUPLED
NUMBER OF BAYS	30	36	-	30	30	36	-	30
SOLAR ARRAY								
NUMBER OF PANELS	60	72	-	60	58	70	-	60
PANEL DIMENSION (METERS)	650W×730L	650W×690L	1.83D (×2)	650W×700L	650L×490L	650W×465L	1.63D (×2)	650W×470L
AREA ($\times10^6$ M^2)	28.47	32.29	5.26	27.3	18.13	21.16	4.17	18.33
GEN. POWER (GW)	9.94	11.46	4.82	9.8	9.94	11.46	6.11	9.8
ANTENNA								
TYPE	KLYSTRON	SOLID STATE	SOLID STATE	MAGNETRON	KLYSTRON	SOLID STATE	SOLID STATE	MAGNETRON
POWER OUTPUT (GW)	7.14	7.36	3.66	8.00	7.14	7.36	4.64	8.0
ILLUMINATION	10 dB GAUS.	10 dB GAUS.	UNIFORM	10 dB HANSEN	10 dB GAUS.	10 dB GAUS.	UNIFORM	10 dB HANSEN
APERTURE (KM)	~1.0	1.35	1.83 (×2)	0.92	~1.0	1.35	1.63 (×2)	0.92
UTILITY INTERFACE POWER (GW)	5.07	5.22	2.42	5.6	5.07	5.22	3.06	5.6
NO. OF SATELLITES ($P_T \lesssim 300$ GW)	60	58	125	54	60	58	98	54
MASS DENSITY (KG/KW_{UI})*	6.24	7.66	8.51	4.77	5.12	6.81	5.35	3.85

$^*KW_{UI}$ = KILOWATTS AT UTILITY INTERFACE NETWORK

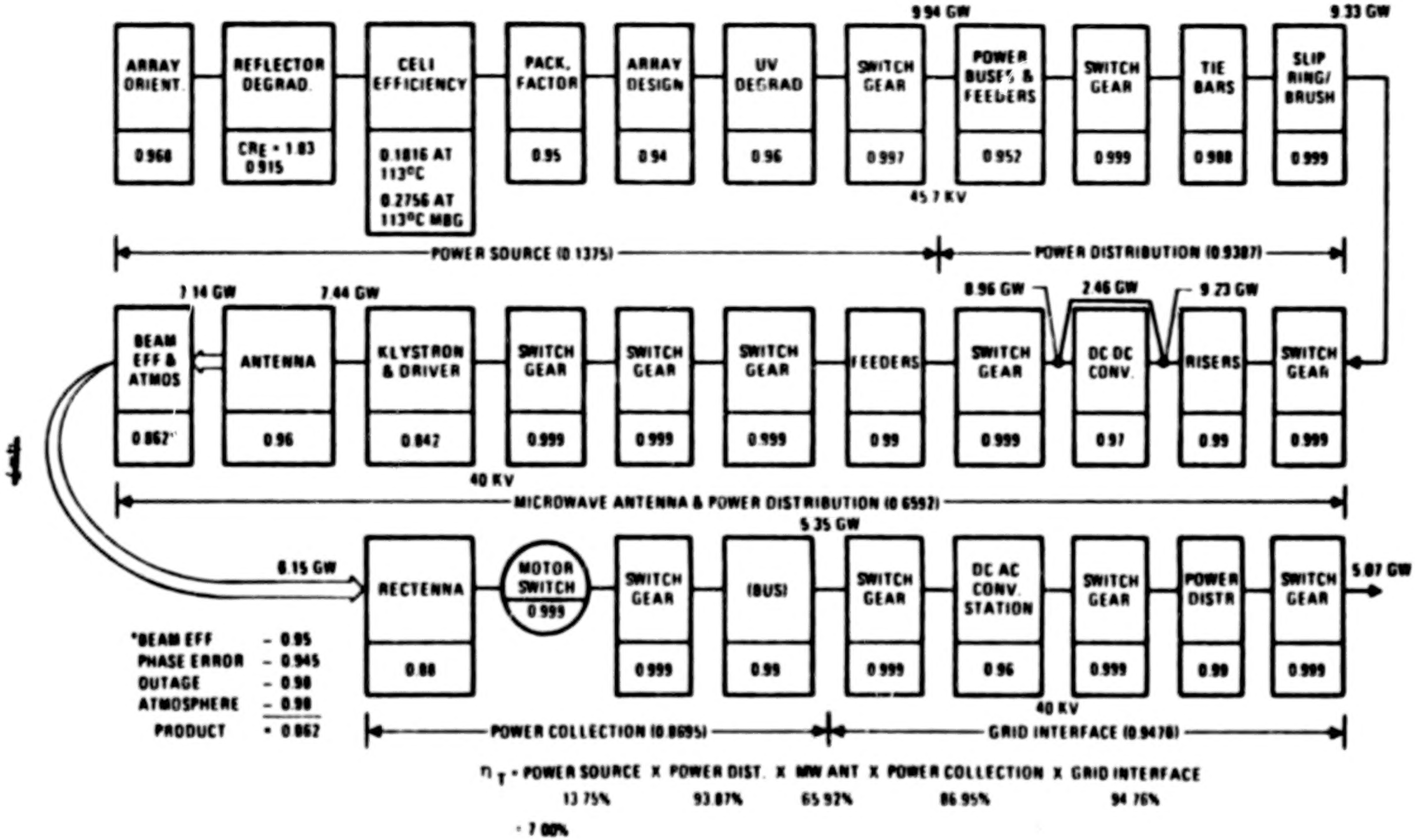

Figure 4.2-1. System Efficient Chain—Reference Concept (April 1980)

Table 4.2-2. Mass Properties—Reference Concept (April 1980)*

		STANDARD CELL GaAs	MBG CELL GaAlAs/GaAs
1.1.1	ENERGY CONVERSION (SOLAR ARRAY)		
	STRUCTURE	1.514	1.133
	PRIMARY	(0.928)	(0.804)
	SECONDARY	(0.586)	(0.329)
	MECHANISMS	0.070	0.070
	CONCENTRATOR	1.030	0.648
	SOLAR PANEL	7.174	4.804
	POWER DISTRIBUTION & CONTROL	2.757	1.388
	PWR COND. EQUIP. & BATT.	(0.319)	(0.206)
	POWER DISTRIBUTION	(2.438)	(1.182)
	THERMAL	NONE	NONE
	MAINTENANCE	0.052	0.063
1.1.3 (PARTIAL)	INFORMATION MANAGEMENT & CONTROL	0.050	0.050
	DATA PROCESSING	(0.021)	(0.021)
	INSTRUMENTATION	(0.029)	(0.029)
1.1.4 (PARTIAL)	ATTITUDE CONTROL	0.116	0.116
	SUBTOTAL	12.803	8.272
1.1.2	POWER TRANSMISSION (ANTENNA)		
	STRUCTURE	0.838	0.838
	PRIMARY	(0.023)	(0.023)
	SECONDARY	(0.815)	(0.815)
	MECHANISM	0.002	0.002
	SUBARRAY	7.050	7.050
	POWER DISTRIBUTION & CONTROL	2.453	2.453
	POWER COND. & BATT.	(1.680)	(1.680)
	POWER DISTRIBUTION	(0.773)	(0.773)
	THERMAL	0.720	0.720
	ANTENNA CONTROL ELECTRONICS	0.170	0.170
	MAINTENANCE	0.107	0.107
1.1.3 (PARTIAL)	INFORMATION MANAGEMENT & CONTROL	0.640	0.640
	DATA PROCESSING	(0.380)	(0.380)
	INSTRUMENTATION	(0.260)	(0.260)
1.1.4 (PARTIAL)	ATTITUDE CONTROL	NEGLIGIBLE	NEGLIGIBLE
	SUBTOTAL	11.980	11.980
1.1.6	INTERFACE		
	STRUCTURE	0.170	0.170
	PRIMARY	(0.136)	(0.136)
	SECONDARY	(0.034)	(0.034)
	MECHANISMS	0.033	0.033
	POWER DISTRIBUTION & CONTROL	0.288	0.288
	POWER DISTRIBUTION	(0.271)	(0.271)
	SLIP RING BRUSHES	(0.017)	(0.017)
	THERMAL	NONE	NONE
	MAINTENANCE	0.032	0.032
	COMMUNICATION	TBD	TBD
	SUBTOTAL	0.523	0.523
	SPS TOTAL (DRY)	25.306	20.775
	GROWTH (25%)	6.326	5.194
	TOTAL SPS (DRY) WITH GROWTH	31.632	25.969
	SATELLITE POWER @ UTILITY INTERFACE (GW)	5.07	5.07
	SATELLITE DENSITY, KG/KW_{UI}	6.24	5.12

* 10^6 kg

exclusive of antenna. Each antenna installation adds 2325 m. Thus, the overall length is 22.650 m (16,650 m for MBG).

Table 4.2-3. Recommended End-Mounted Solid-State Antenna Concept Characteristics

- GaAs SOLAR ARRAY
- GEOMETRIC CR = 2.0
- DUAL END-MOUNTED MICROWAVE ANTENNAS
- AMPLIFIER BASE TEMPERATURE = 125°C
- AMPLIFIER EFFICIENCY = 0.8
- ANTENNA POWER TAPER = 10 dB
- ANTENNA DIAMETER = 1.35 km
- POWER AT UTILITY INTERFACE = 2.61 GW PER ANTENNA (5.22 GW TOTAL)
- RECTENNA BORESIGHT DIAMETER = 7.45 km PER RECTENNA

Blanket dimensions are 650 m wide by 690 m long (650 465 m for MBG cells). Total area is 32.3×10^6 m^2 for the single-junction cell configuration, and 21.2×10^6 m^2 for the dual-junction (MBG) cell configuration. The antennas shown both utilize a 10 dB Gaussian shaped beam pattern to minimize side lobe power levels. Total power output from each half of the area is estimated as 5.73 GW. Total power transmitted from each antenna is estimated to be 3.68 GW. Total transmission power from the satellite is, therefore, 7.76 GW. System efficiencies for these configurations are shown in Figure 4.2-2.

Table 4.2-4 presents a summary of the mass properties for these configurations.

4.2.3 SANDWICH CONCEPT SOLID-STATE ANTENNA

The solid-state sandwich antenna system concept is illustrated in Figure 4.1-3. The system consists of dual mirror configurations focusing solar energy upon the rear-mounted solar cell blankets of the dual integrated solar cell/power transmitting antenna (sandwich). The primary mirror is pivoted and may be rotated about the reflected solar axis so that antenna will remain locked to the antenna/rectenna boresight while maintaining the solar pointing during the 24-hour earth rotation and the ±23.5° variation in the solar/equatorial plane.

Characteristics of the single- and multi-junction based antenna sandwich are summarized in Table 4.2-5. Total solar area of 2.63×10^6 m^2 and 2.09×10^6 m^2 is available. In this configuration, solar cell area and antenna aperture area are the same. System efficiencies for these configurations are shown in Figure 4.2-3.

Table 4.2-6 presents a summary of the mass properties of both solar cell variations of the dual sandwich configuration.

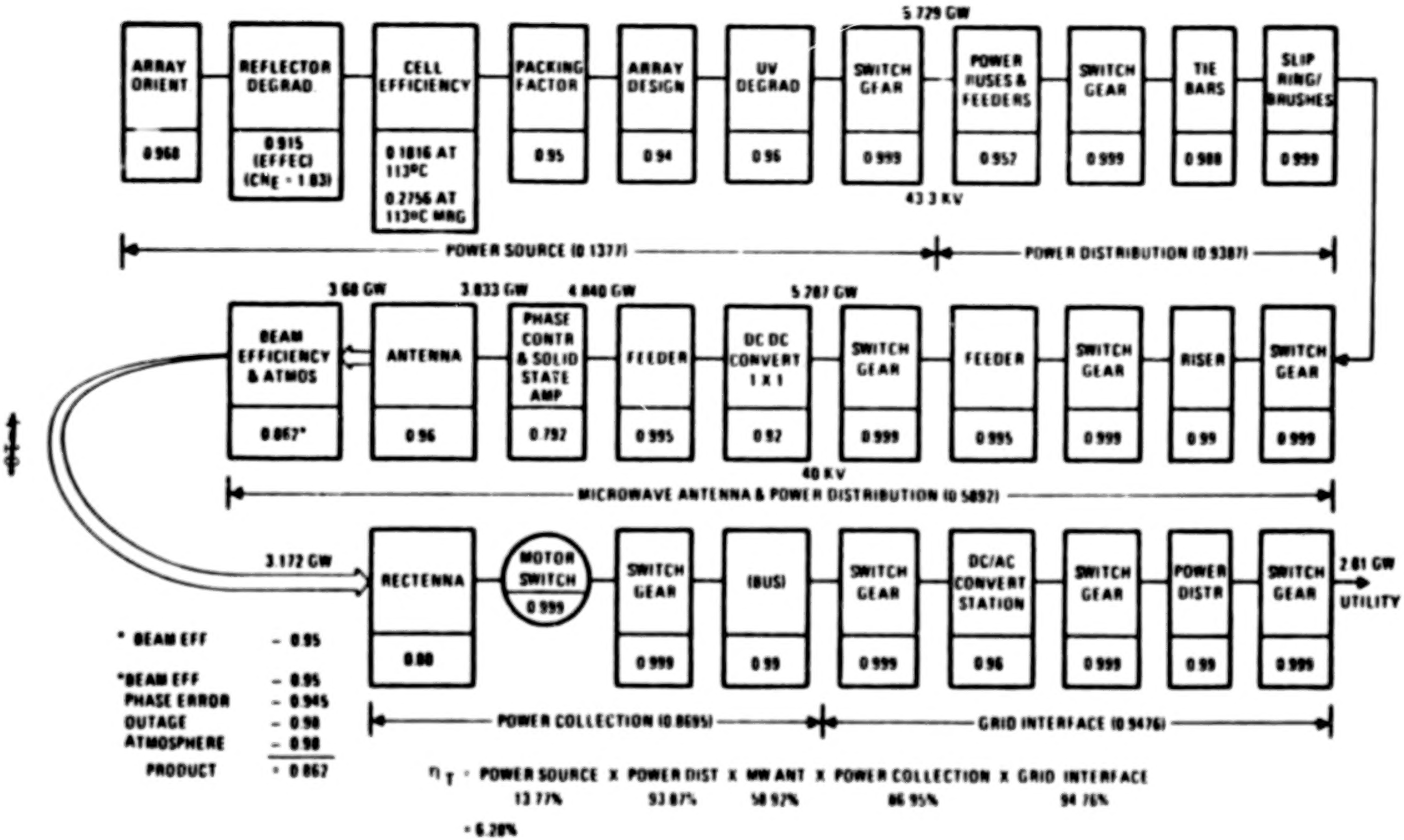

Figure 4.2-2. System Efficiency Chain Dual End-Mounted Concept (Solid State Antenna) (April 1980)

Table 4.2-4. Mass Properties, Dual End-Mounted Solid-State Antenna

		STD CELL GaAs	MBG CELL GaAlAs/GaAs
1.1.1	ENERGY CONVERSION (SOLAR ARRAY)		
	STRUCTURE	1.496	1.233
	PRIMARY	(1.077)	(0.902)
	SECONDARY	(0.419)	(0.331)
	MECHANISMS	0.087	0.078
	CONCENTRATOR	1.169	0.766
	SOLAR PANEL	8.138	5.607
	POWER DISTRIBUTION AND CONTROL	1.112	0.846
	POWER COND. EQUIP. & BATT.	(0.102)	(0.222)
	POWER DISTRIBUTION	(1.010)	(0.624)
	THERMAL	NONE	NONE
	MAINTENANCE	0.104	0.056
1.1.3 (PARTIAL)	INFORMATION MANAGEMENT AND CONTROL	0.057	0.057
	DATA PROCESSING	(0.024)	(0.024)
	INSTRUMENTATION	(0.033)	(0.033)
1.1.4 (PARTIAL)	ATTITUDE CONTROL	0.116	0.116
	SUBTOTAL	12.279	8.759
1.1.2	POWER TRANSMISSION (ANTENNA)		
	STRUCTURE	1.409	1.409
	PRIMARY	(0.094)	(0.094)
	SECONDARY	(1.315)	(1.315)
	MECHANISM	0.004	0.004
	SUBARRAY	10.561	10.561
	POWER DISTRIBUTION AND CONTROL	4.405	4.405
	POWER CONDITIONING & BATT.	(2.164)	(2.164)
	POWER DISTRIBUTION	(2.241)	(2.241)
	THERMAL	NONE	NONE
	ANTENNA CONTROL ELECTRONICS	0.340	0.340
	MAINTENANCE	0.448	0.448
1.1.3 (PARTIAL)	INFORMATION MANAGEMENT AND CONTROL	1.622	1.662
	DATA PROCESSING	(1.385)	(1.385)
	INSTRUMENTATION	(0.237)	(0.237)
1.1.4 (PARTIAL)	ATTITUDE CONTROL	NEGLIG.	NEGLIG.
	SUBTOTAL	18.789	18.789
1.1.6	INTERFACE		
	STRUCTURE	0.236	0.236
	PRIMARY	(0.168)	(0.168)
	SECONDARY	(0.068)	(0.068)
	MECHANISMS	0.072	0.072
	POWER DISTRIBUTION AND CONTROL	0.538	0.538
	POWER DISTRIBUTION	(0.487)	(0.487)
	SLIP RING BRUSHES	(0.051)	(0.051)
	THERMAL	NONE	NONE
	MAINTENANCE	0.064	0.064
	COMMUNICATION	TBD	TBD
	SUBTOTAL	0.910	0.910
	SPS TOTAL (DRY)	31.978	28.458
	GROWTH (25%)	7.995	7.114
	TOTAL SPS (DRY) WITH GROWTH	39.973	35.572
	SATELLITE POWER @ UTILITY INTERFACE (GW)	5.22	5.22
	SATELLITE DENSITY, KG/KW_{UI}	7.66	6.81

Table 4.2-5. Nominal Characteristics of Sandwich Concepts

	GaAs	GaAlAs/GaAs
UNIFORM ILLUMINATION	(0 dB TAPER)	(0 dB TAPER)
EFFECTIVE (CR_E)	5.2	5.2
SOLAR CELL TEMPERATURE	200°C	200°C
SOLAR CELL EFFICIENCY	0.1566	0.2506
AMPLIFIER EFFICIENCY	0.8	0.8
AMPLIFIER BASE TEMPERATURE	125°C	125°C
ANTENNA OHMIC EFFICIENCY	0.96	0.96
SOLAR CELL PACKING FACTORS	0.8547	0.8547
POWER TRANSMITTED/UNIT AREA	778.9 w/m^2	1242 w/m^2
ANTENNA DIAMETER	1.83 km	1.63 km
ANTENNA AREA	2.63 km^2	2.09 km^2
TOTAL TRANSMITTED POWER	3.66 GW	4.64 GW
POWER AT UTILITY INTERFACE (EA.)	1.21 GW	1.53 GW
RECTENNA AXIS (EACH)	4.87-5.99 km	5.47-7.16 km
RECTENNA AREA (EACH)	23.2 km^2	31.3 km^2
ANTENNA DETAIL		
TYPE—DIPOLE WITH DIPOLE-MOUNTED AMPLIFIERS		
• ELEMENT SPACING	7.32 cm	7.81 cm
• NUMBER OF ELEMENTS/SQUARE METER	164	164
• OUTPUT POWER/DEVICE	4.24 W	6.77 W
• HEAT DISSIPATED DEVICE	1.06 W	1.69 W
• GROUND PLANE TO DIPOLE LENGTH	3.05 cm	3.05 cm
• BERLOX DISC DIAMETER	4.46 cm	6.09 cm
• BERLOX DISC AREA	15.62 cm^2	29.1 cm^2
• BERLOX DISC THICKNESS	0.0254 cm	0.0254 cm
• BERLOX DISC VOLUME	0.397 cm^3	0.740 cm^3

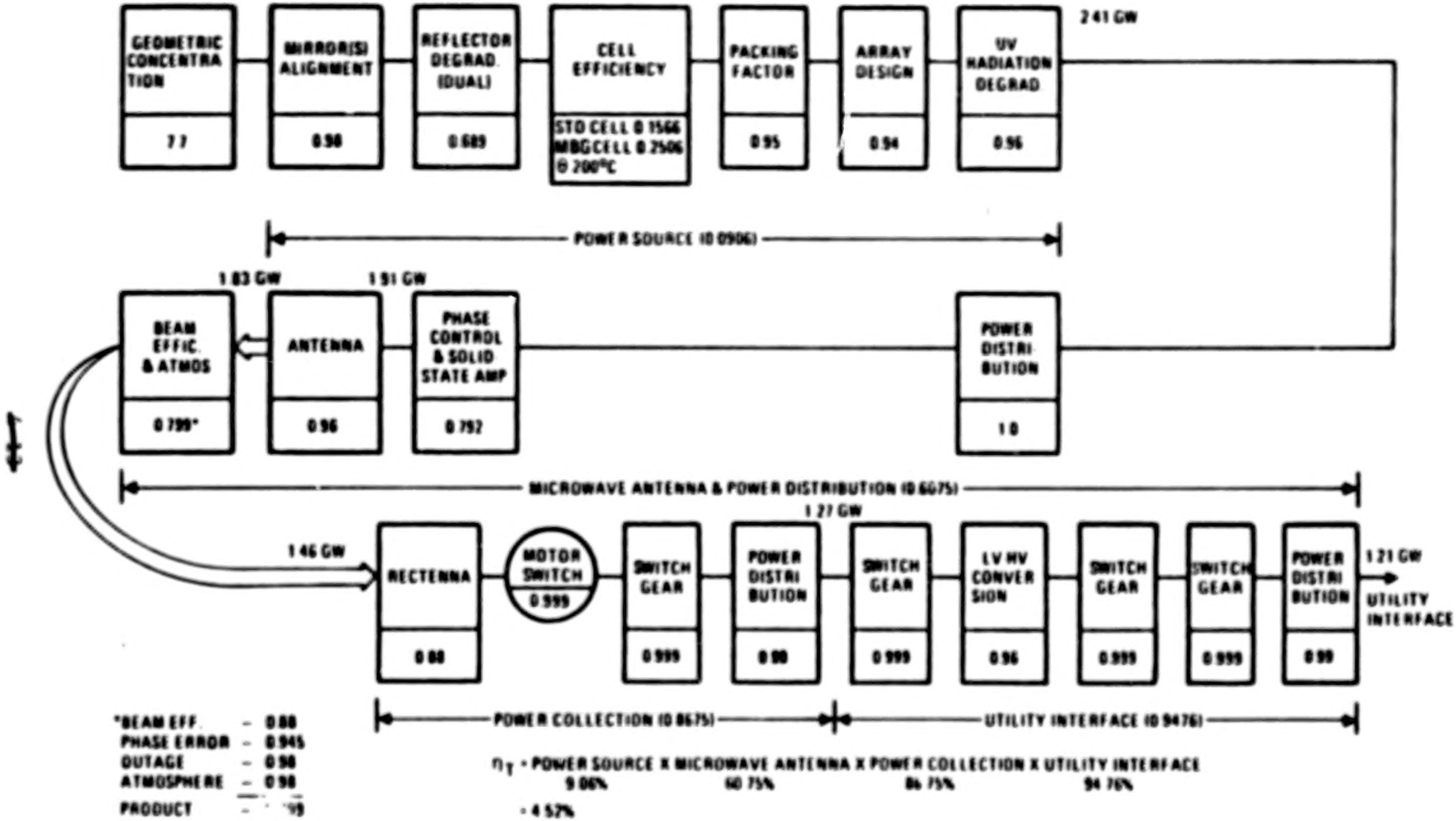

Figure 4.2-3. System Efficiency Chain—Sandwich Concept (Solid-State Antenna) (April 1980)

Table 4.2-6. Mass Properties, Dual Sandwich Solid-State Antenna

		STD CELL GaAs	MBG CELL GaAlAs/GaAs
1.1.1	ENERGY CONVERSION (SOLAR ARRAY)		
	STRUCTURE	3.412	2.411
	PRIMARY	(3.026)	(2.138)
	SECONDARY	(0.386)	(0.273)
	MECHANISMS	0.027	0.019
	CONCENTRATOR	2.075	1.646
	SOLAR PANEL	0.076*	0.076*
	POWER DISTRIBUTION AND CONTROL	0.015	0.015
	POWER COND. EQUIP. & BATT.	(0.013)	(0.013)
	POWER DISTRIBUTION	(0.002)	(0.002)
	THERMAL	NONE	NONE
	MAINTENANCE	0.100	0.100
1.1.3 (PARTIAL)	INFORMATION MANAGEMENT AND CONTROL	0.033**	0.033**
	DATA PROCESSING	(0.014)	(0.014)
	INSTRUMENTATION	(0.019)	(0.019)
1.1.4 (PARTIAL)	ATTITUDE CONTROL	0.103	0.103
	SUBTOTAL	5.841	4.403
1.1.2	POWER TRANSMISSION (ANTENNA)		
	STRUCTURE	0.729	0.649
	PRIMARY	(0.161)	(0.143)
	SECONDARY	(0.568)	(0.506)
	MECHANISM	NONE	NONE
	SUBARRAY	8.821	7.053
	POWER DISTRIBUTION AND CONTROL	INCLUDED	INCLUDED
	THERMAL	NONE	NONE
	ANTENNA CONTROL ELECTRONICS	0.340	0.340
	MAINTENANCE	0.436	0.408
1.1.3 (PARTIAL)	INFORMATION MANAGEMENT & CONTROL	0.256***	0.256***
	DATA PROCESSING	(0.152)	(0.152)
	INSTRUMENTATION	(0.104)	(0.104)
1.1.4 (PARTIAL)	ATTITUDE CONTROL	NEGLIG.	NEGLIG.
	SUBTOTAL	10.582	8.706
1.1.6	INTERFACE		
	STRUCTURE	N/A	N/A
	PRIMARY		
	SECONDARY		
	MECHANISMS	N/A	N/A
	POWER DISTRIBUTION AND CONTROL	N/A	N/A
	POWER DISTRIBUTION		
	SLIP RING BRUSHES		
	THERMAL	N/A	N/A
	MAINTENANCE	-	-
	COMMUNICATION	TBD	TBD
	SUBTOTAL	-	-
	SPS TOTAL (DRY)	16.423	13.109
	GROWTH (25%)	4.106	3.277
	TOTAL SPS (DRY) WITH GROWTH	20.529	16.386
	SAT. PWR @ UTILITY INTERFACE (GW)	2.41	3.06
	SAT. DENSITY, KG/KW$_{UI}$	8.52	5.35

*AUXILIARY POWER ONLY
**TWO-THIRDS MASS OF REFERENCE CONCEPT
***20% REF. MASS PER ANTENNA

4.2.4 MAGNETRON CONCEPT

The satellite concept using magnetrons as microwave power amplifiers on the antenna is physically similar to the klystron based concept and, therefore, has the same general configuration as the reference concept (Figure 4.1-1). The array length of the concept based upon a 20-kV (nominal) solar array voltage is 15,000 m (10,000 m, MBG). Overall length including the antenna is 16,900 m (11,900 m, MBG).

The solar array panels are 700 m long and 650 m wide, and generate 21.85 kV at the switch gear output. The solar array panels with MBG cells are 470 m long. As was the case with the klystron concept, the 650-m width consists of 26 strips, each 25 m wide. Total power from the solar output is estimated to be 9.8 GW. Total transmitted power is calculated to be 8.00 GW. System efficiency factors for this configuration are indicated in Figure 4.2-4.

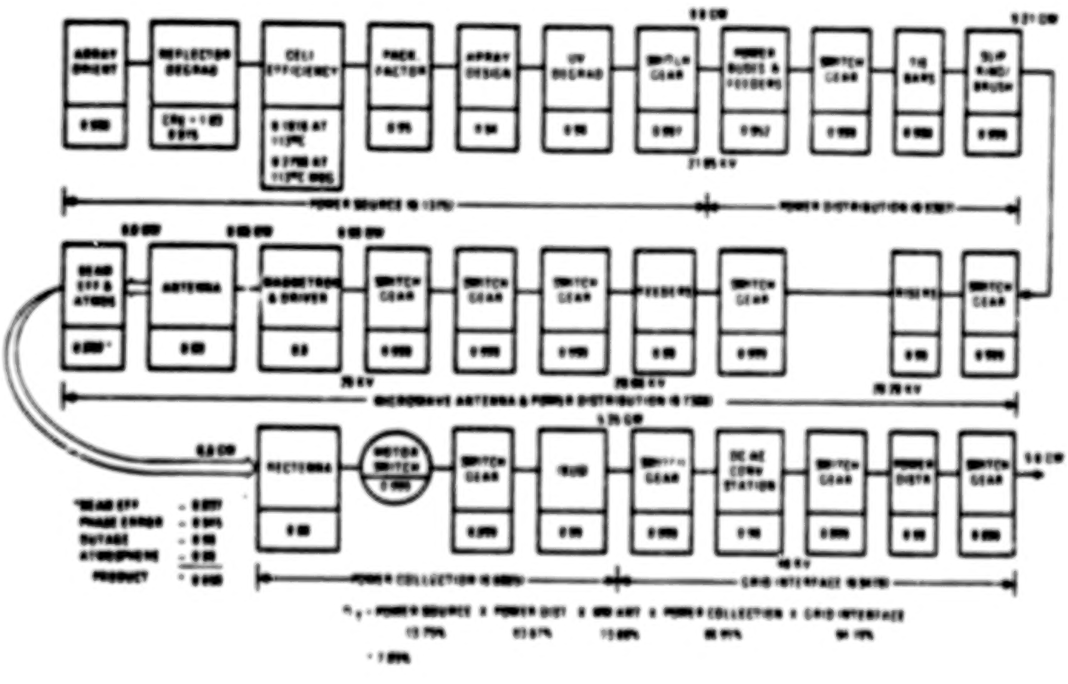

Figure 4.2-4. System Efficiency Chain—Magnetron Concept (June 1980).

Table 4.2-7 summarizes the satellite mass properties.

Table 4.2-7. Mass Properties—Magnetron Antenna (April 1980)

	STD CELL GaAs	MBG CELL GaAlAs/GeAs
	**	**
1.1.1 ENERGY CONVERSION (SOLAR ARRAY)		
STRUCTURE	1.601	1.245
PRIMARY	(0.904)	(0.565)
SECONDARY	(0.697)	(0.680)
MECHANISMS	0.070	0.070
CONCENTRATOR	0.986	0.663
SOLAR PANEL	6.850	4.619
POWER DISTRIBUTION & CONTROL	4.146	2.874
POWER COND. EQUIP. & BATT.	(0.319)	(0.319)
POWER DISTRIBUTION	(3.827)	(2.555)
THERMAL	NONE	NONE
MAINTENANCE	0.092	0.092
1.1.3* INFORMATION MANAGEMENT & CONTROL	0.050	0.050
DATA PROCESSING	(0.021)	(0.021)
INSTRUMENTATION	(0.029)	(0.029)
1.1.4* ATTITUDE CONTROL	0.116	0.116
SUBTOTAL	13.943	9.729
1.1.2 POWER TRANSMISSION (ANTENNA)		
STRUCTURE	0.547	0.547
PRIMARY	(0.023)	(0.023)
SECONDARY	(0.524)	(0.524)
MECHANISM	0.002	0.002
SUBARRAY	3.320	3.320
POWER DISTRIBUTION & CONTROL	1.515	1.515
POWER CONDITIONING & BATT.	(0.346)	(0.346)
POWER DISTRIBUTION	(1.169)	(1.169)
THERMAL	NONE	NONE
ANTENNA CONTROL ELECTRONICS	0.170	0.170
MAINTENANCE	0.107	0.107
1.1.3* INFORMATION MANAGEMENT AND CONTROL	0.320	0.320
DATA PROCESSING	(0.190)	(0.190)
INSTRUMENTATION	(0.130)	(0.130)
1.1.4* ATTITUDE CONTROL	NEGLIG.	NEGLIG.
SUBTOTAL	5.981	5.981
1.1.6 INTERFACE		
STRUCTURE	0.257	0.257
PRIMARY	(0.136)	(0.136)
SECONDARY	(0.121)	(0.121)
MECHANISMS	0.033	0.033
POWER DISTRIBUTION & CONTROL	1.194	1.194
POWER DISTRIBUTION	(1.177)	(1.177)
SLIP RING BRUSHES	(0.017)	(0.017)
THERMAL	NONE	NONE
MAINTENANCE	0.032	0.032
COMMUNICATION	TBD	TBD
SUBTOTAL	1.516	1.516
SPS TOTAL (DRY)	21.44	17.226
GROWTH (25%)	5.36	4.307
TOTAL SPS (DRY) WITH GROWTH	26.8	21.533
SAT. PWR @ UTILITY INTERFACE (GW)	5.6	5.6
SATELLITE DENSITY, KG/KW$_{UI}$	4.79	3.85

*PARTIAL **10^6 KG

4.3 TRANSPORTATION

4.3.1 INTRODUCTION

During the several phases of the SPS Concept Definition Study, various transportation system elements were synthesized and evaluated on the basis of their potential to satisfy overall SPS transportation requirements and of their sensitivities, interfaces, and impact on the SPS.

Additional analyses and investigations were conducted to further define transportation system concepts that will be needed for the developmental and operational phases of an SPS program. To accomplish these objectives, transportation systems such as the Shuttle and its derivatives have been identified; new heavy-lift launch vehicle (HLLV) concepts, cargo and personnel orbital transfer vehicles (EOTV and POTV), and intra-orbit transfer vehicle (IOTV) concepts have been evaluated; and, to a limited degree, the program implications of their operations and costs were assessed. The results of these analyses have been integrated into other elements of the overall SPS concept definition studies.

The primary areas of study during this phase of the contract were directed toward the following:

- The synthesis and evaluation of a smaller payload version of the HLLV

- The assessment of specific technical issues relating to HLLV feasibility

- A reassessment of the EOTV concept and configuration update

- The identificatwon of technology advancement requirements to enhance/satisfy operations requirements

- The generation of cost and programmatic data to support SPS concept trade studies

SPS program and transportation system analyses continue to show that the prime element of transportation systems cost, and SPS program cost, is that of payload delivery to LEO or HLLV feasibility/cost.

4.3.2 TRANSPORTATION SYSTEM ELEMENTS

Studies conducted to date definitely show that the SPS program will require a dedicated transportation system. In addition, because of the high launch rate requirements and environmental considerations, a dedicated launch facility may also be required during the SPS construction phase. The major elements of the SPS transportation system consist of:

- Heavy-Life Launch Vehicle (HLLV)—SPS cargo to LEO
- Personnel Transfer Vehicle (PTV)—personnel to LEO (Growth STS)

• Electric Orbit Transfer Vehicle (EOTV)—SPS cargo to GEO
• Personnel Orbit Transfer Vehicle (POTV)—personnel from LEO to GEO
• Personnel Module (PM)—personnel carrier from earth-LEO-GEO
• Intra-Orbit Transfer Vehicle (IOTV)—on-orbit transfer of cargo/personnel

Of the many HLLV options investigated (i.e., one- and two-stage ballistic or winged, parallel or series burn, etc.), a two-stage vertical takeoff horizontal landing (VTO/HL) HLLV (Figure 4.3-1) has been tentatively selected as the preferred or "baseline" concept. An interim HLLV will be required during the initial SPS program development phase (Figure 4.3-2). This vehicle is designated as a Shuttle-derived or "Growth Shuttle" HLLV (STS-HLLV). This launch vehicle utilizes the same elements as the PLV (described below), except the orbiter is replaced with a payload module and an auxiliary recoverable engine module to provide a greater cargo capability.

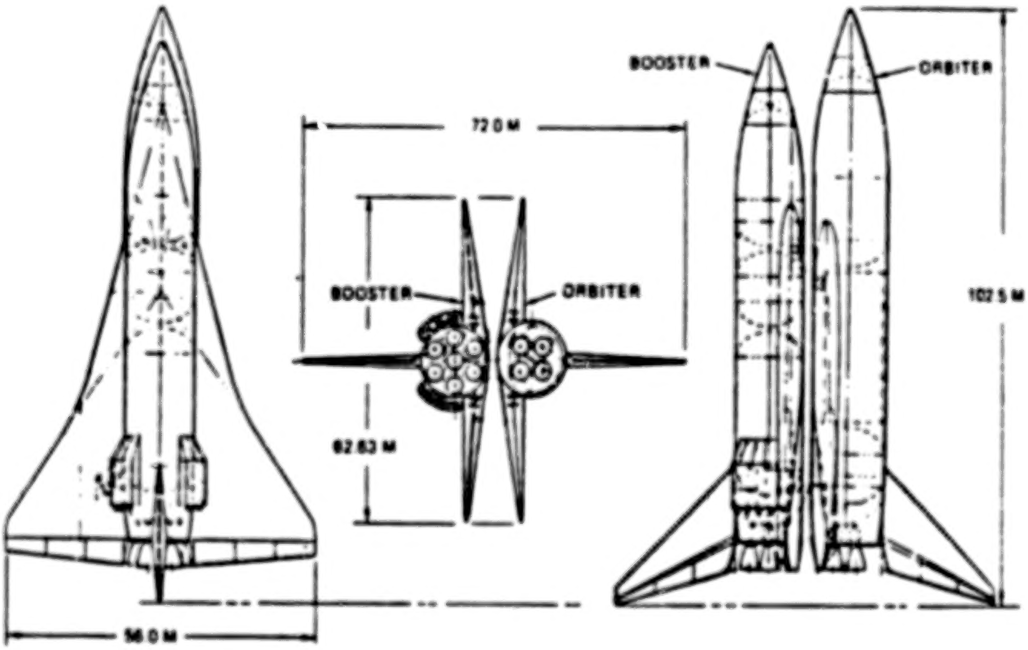

Figure 4.3-1. VTO/HL HLLV Concept

The personnel launch vehicle (PLV) is used to transfer the SPS construction crew from earth to LEO. This launch vehicle is a modified Shuttle Transportation System (STS) configuration. The existing STS solid rocket boosters (SRB) are replaced with reusable liquid rocket boosters (LRB), thus affording a greater payload capability and lower overall operating cost (Figure 4.3-3). The personnel module, described below, is designed to fit within the existing STS orbiter cargo bay.

The interim HLLV and PTV (STS derivatives) will be phased out of the program when the SPS dedicated HLLV becomes operational.

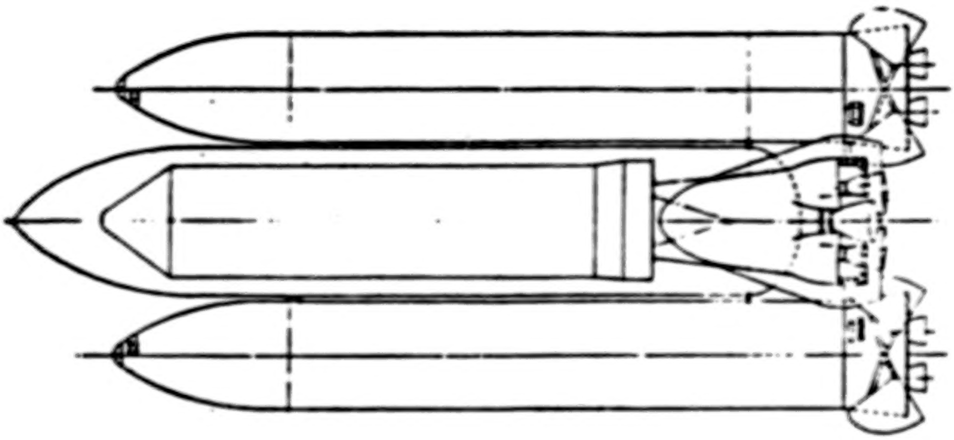

Figure 4.3-2. STS-HLLV Configuration

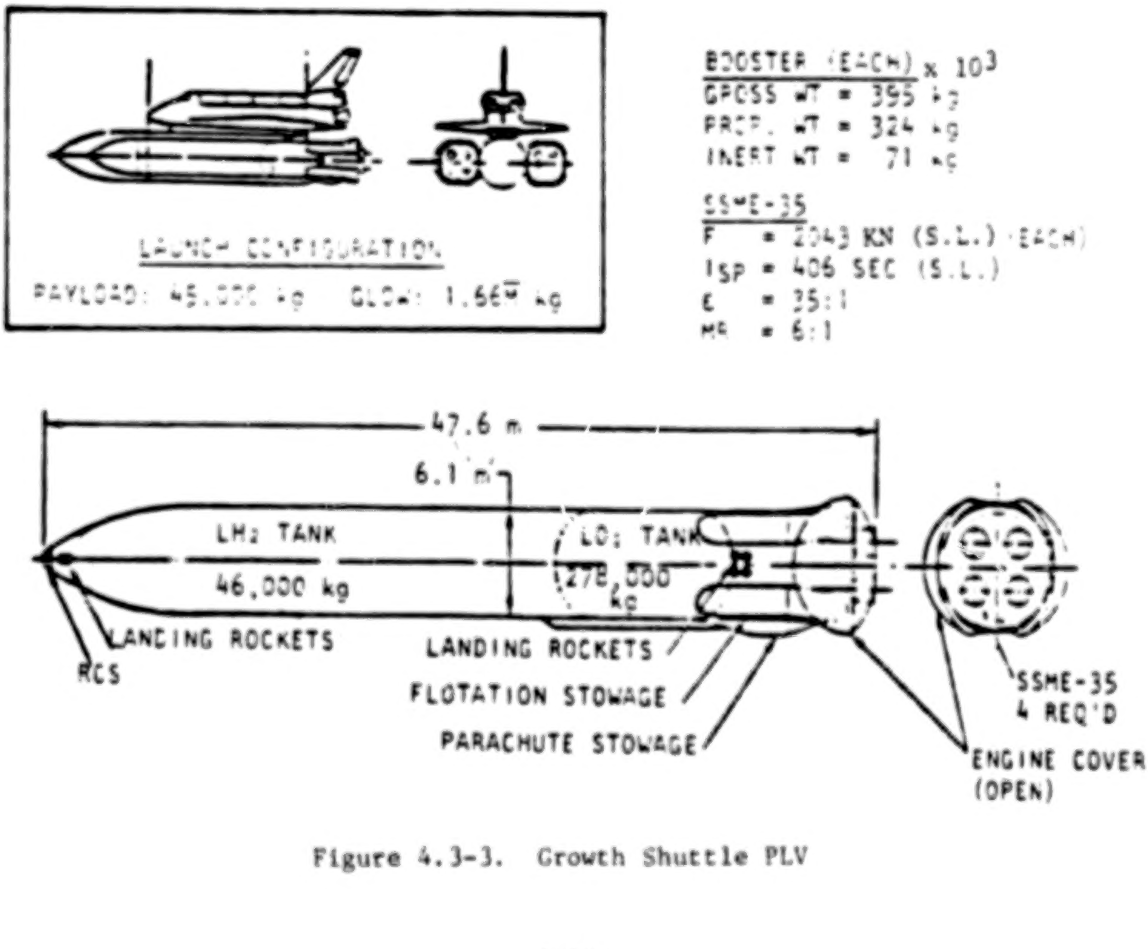

Figure 4.3-3. Growth Shuttle PLV

The electric orbital transfer vehicle (EOTV) is employed as the primary transportation element for SPS cargo from LEO to GEO. The vehicle configuration (Figure 4.3-4), defined to accomplish this mission phase, utilizes the same power source and construction techniques as the SPS. The solar array consists of two "bays" of the SPS, electric argon ion engine arrays, and the requisite propellant storage and power conditioning equipment. The vehicle configuration, payload capability, and "trip time" have been established on the basis of overall SPS compatibility.

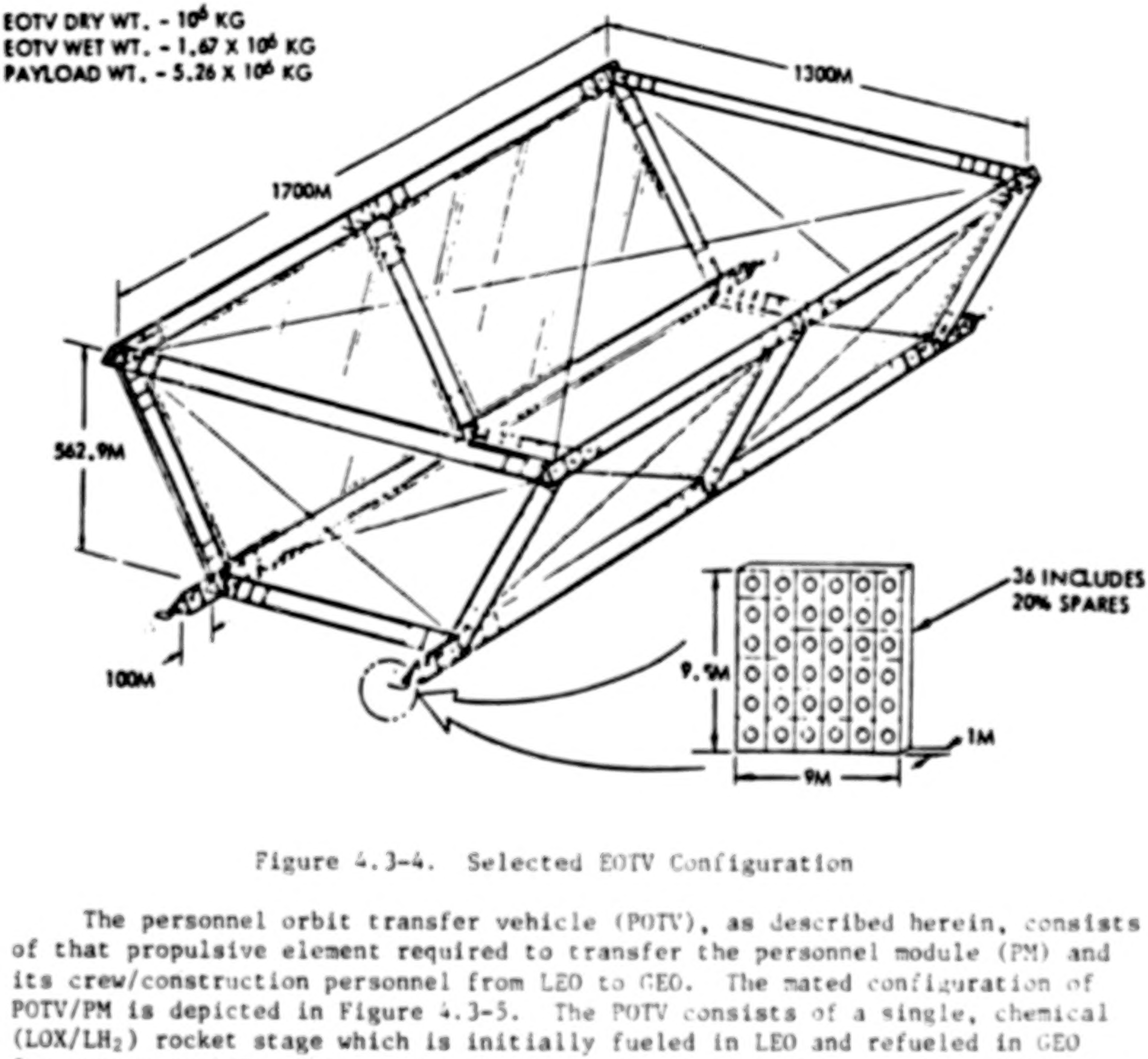

Figure 4.3-4. Selected EOTV Configuration

The personnel orbit transfer vehicle (POTV), as described herein, consists of that propulsive element required to transfer the personnel module (PM) and its crew/construction personnel from LEO to GEO. The mated configuration of POTV/PM is depicted in Figure 4.3-5. The POTV consists of a single, chemical (LOX/LH_2) rocket stage which is initially fueled in LEO and refueled in GEO for return to LEO. The POTV has been sized such that it is capable of fitting within the existing STS cargo bay and the growth STS payload delivery capability.

An intra-orbit transfer vehicle (IOTV) is defined in concept only. Because of the potential problems associated with docking and cargo transfer between the HLLV and EOTV in LEO and the EOTV and GEO construction base, a transfer vehicle capable of accomplishing this function is postulated. From cost and programmatic aspects of the overall SPS program, this element is depicted as a chemical rocket stage, manned or remotely operated.

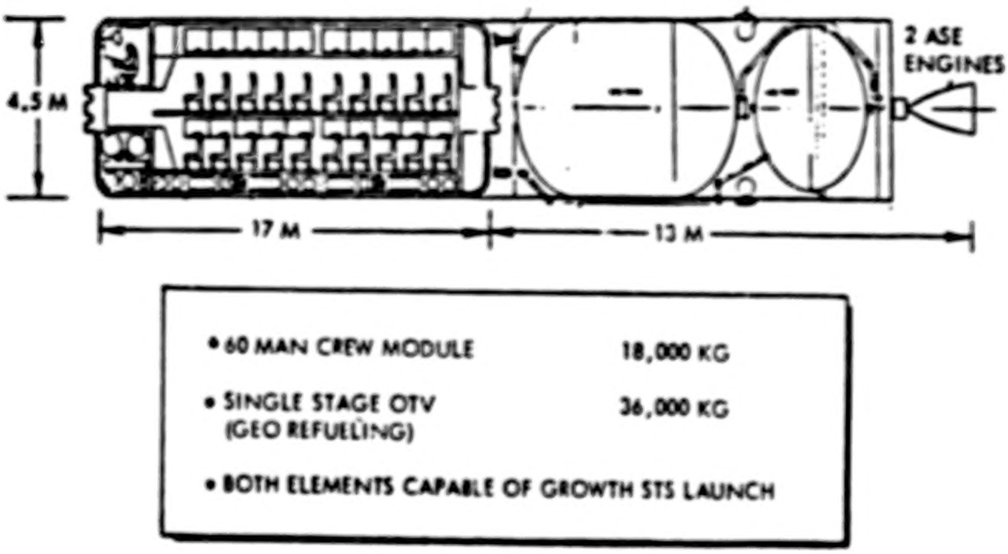

Figure 4.3-5. POTV Configuration

4.3.3 TRANSPORTATION SYSTEM SCENARIO

As previously stated, the SPS will require a dedicated transportation system. In addition, because of the high launch rates and certain environmental considerations, it appears that a dedicated launch facility may also be required for SPS HLLV launches. Transportation system LEO operations are depicted in Figure 4.3-6. The SPS HLLV delivers cargo and propellants to LEO, which are transferred to a dedicated electric OTV (EOTV) by means of an intra-orbit transfer vehicle (IOTV) for subsequent transfer to GEO.

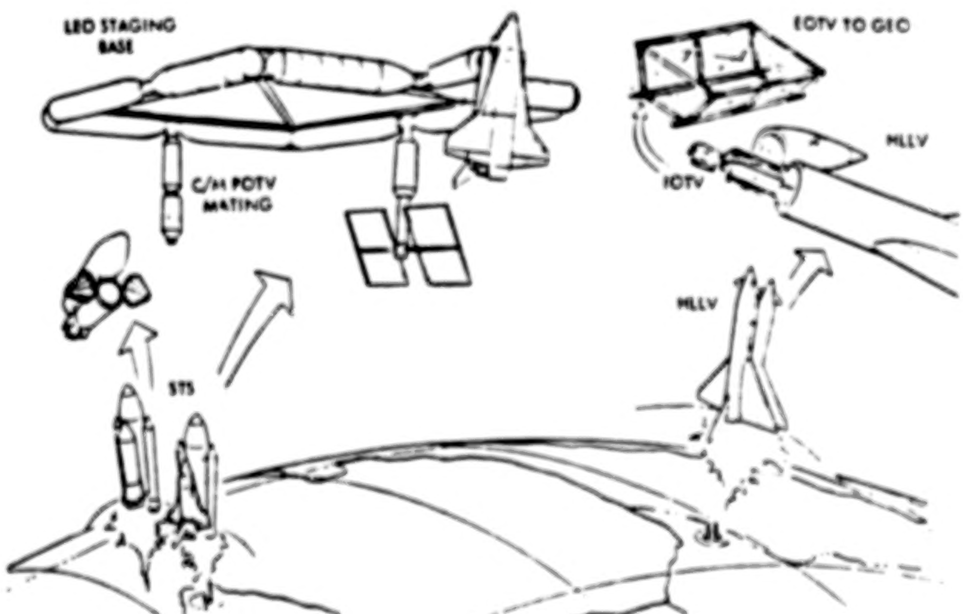

Figure 4.3-6. SPS LEO Transportation Operations

Space Shuttle transportation system derivatives (heavier payload capability) are employed for crew transfer from earth to LEO. The Shuttle-derived HLLV is employed early in the program for space base and precursor satellite construction and delivery of personnel orbit transfer vehicle (POTV) propellants. These elements of the transportation system are phased out of the program with initiation of first satellite construction, or sooner.

Transportation system GEO operations are depicted in Figure 4.3-7. Upon arrival at GEO, the SPS construction cargo is transferred from the EOTV to the SPS construction base by IOTV. The POTV with crew module docks to the construction base to effect crew transfer and POTV refueling for return flight to LEO. Crew consumables and resupply propellants are transported to GEO by the EOTV.

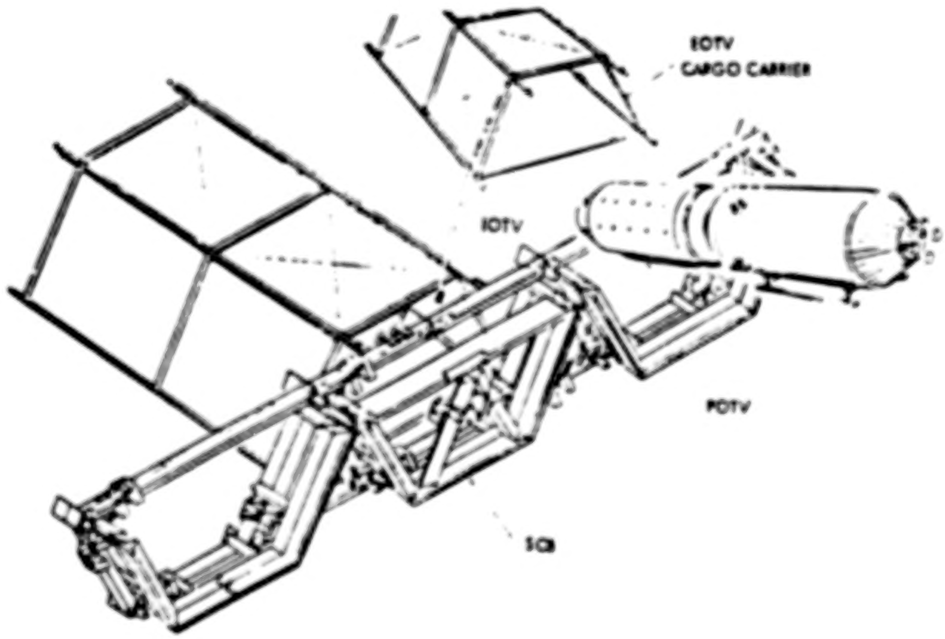

Figure 4.3-7. SPS GEO Transportation Operations

Transportation system requirements are dominated by the vast quantity of materials to be transported to LEO and GEO. Tables 4.3-1, 4.3-2, and 4.3-3 summarize the mass delivery requirements and numbers of vehicle flights for the reference satellite and transportation elements. All mass figures include a 10% packaging factor. Table 4.3-1 summarizes transportation requirements

Table 4.3-1. GaAs Reference SPS Concept—
Pilot Plant Transportation Requirements

		VEHICLE FLIGHTS			
	MASS-10^6 kg	STS (PLV)	STS (CARGO)	STS-GROWTH (PLV)	STS-HLLV (CARGO)
PRECURSOR	2.019	6	79	-	-
LEO BASE	5 MODULES	-	-	-	5
SCB	5.300	-	-	72	58
PROPELLANT	0.864	-	34	-	-
TOTAL	-	6	113	72	63

for construction of the pilot plant satellite. Table 4.3-2 is a summary of requirements for first satellite construction. Table 4.3-3 defines the transportation requirements during the construction phase (i.e., the first 30 years). The average annual mass to LEO during this phase is in excess of 100 million kilograms with more than 400 HLLV launches per year.

Table 4.3-2. GaAs Reference SPS Concept—
TFU Transportation Requirements

	MASS - 10^6 kg		VEHICLE FLIGHTS					
							IOTV	
	LEO	GEO	PLV (MLLV)	HLLV	POTV	EOTV	LEO	GEO
SATELLITE CONSTR. & MAINT.	34.8	34.8	5.4	153.3	40	5.1	215	153
CREW CONSUMABLES	1.5	0.1		6.6		-	7	-
POTV PROPELLANTS	2.9	1.4		12.7		0.2	13	6
EOTV CONSTRUCTION & MAINT.	7.5	-		32.8		-	33	-
EOTV PROPELLANTS	7.6	-		33.5		-	34	-
IOTV PROPELLANTS	0.2	0.1		0.6		-	1	1
SCB TO GEO	-	-		-		2	-	-
TOTAL	54.5	36.4	5	240	40	8	303	160
FLEET	-	-	-	5	4	6	2	2

Table 4.3-3. GaAs Reference SPS Concept—
Total Transportation Requirements, 60-Year Program
(54 Satellites)

	MASS - 10^6 kg		VEHICLE FLIGHTS					
							IOTV	
	LEO	GEO	PLV (MLLV)	HLLV	POTV	EOTV	LEO	GEO
SATELLITE								
CONSTRUCTION	2087.7	2087.7	111	9,197	1220	306.4	10,741	9,197
OPS & MAINT	492.2	492.2	34	2,168	324	72.7	2,560	2,168
CREW CONSUMABLES								
CONSTRUCTION	29.9	28.7		132		4.2	132	126
OPS & MAINT.	9.2	7.6		41		1.1	41	34
POTV PROPELLANTS								
CONSTRUCTION	87.9	44.0		387		5.5	97	194
OPS & MAINT	23.3	11.7		103		1.2	103	52
EOTV CONSTRUCTION								
CONSTRUCTION	19.9	12.4		88		1.8	88	55
OPS & MAINT	5.0	5.0		22		0.7	22	22
EOTV PROPELLANTS								
CONSTRUCTION	306.0	1.9		1,348		0.3	1,348	8
OPS & MAINT	73.0	0.8		322		0.1	322	4
IOTV PROPELLANTS								
CONSTRUCTION	7.4	3.2		33		0.5	33	14
OPS & MAINT	1.8	0.8		8		0.1	8	3
SUMMARY								
CONSTRUCTION	2538.8	2177.9	111	11,185	1220	320	12,729	9,594
OPS & MAINT	604.5	318.1	34	2,664	324	76	3,056	2,283
TOTAL	3143.3	2496.0	145	13,849	1544	396	15,785	11,877
VEHICLE FLEET								
CONSTRUCTION	-	-	-	38	12	16	112	
OPS & MAINT	-	-	-	9	3	4	27	
TOTAL	-	-	-	47	15	20	139	

4.4 SPS PROGRAM COSTS

4.4.1 INTRODUCTION

Five SPS concepts were costed during the Exhibit D contract activity. These configurations fall into two basic categories or "families" as shown in Figure 4.4-1. The three-trough/planar concepts have varying masses averaging 32.7×10^6 kg (with growth) versus 18.5×10^6 kg (with growth) for the reflector/sandwich concepts; however, there is a variable power output at the utility interface for each of these satellites. The objective of this section is to present cost estimates for all of these concepts, and to make a comparative analysis of various systems/subsystems along with a discussion of end-to-end cost data generated during the study.

4.4.2 COSTING GUIDELINES AND GROUND RULES

System and subsystem definitions were developed during the study and expanded by in-depth analyses to provide detailed technical characteristics and design parameters for use in cost-estimating relationships and "grass roots" analyses. The SPS work breakdown structure is organized as shown in Table 4.4-1, and 300 line items have comprised each concept defined. Calculations in each line item were made to provide costs for DDT&E, theoretical first unit (TFU), SPS investment per satellite, and operational phases.

Common guidelines and ground rules became the basis for uniform development of SPS costs. These ground rules were established at the outset of the program development activity and included a management and integration factor of 5% and a 15% cost contingency that allows for a 25% growth in the mass of space-related elements. Costing guidelines and ground rules are summarized as follows:

- SPS option to provide 300-GW capability at the utility interface
- Overall SPS lifetime of 30 years with minimum maintenance
- Key dates for program planning

  1981-1986 - Research and technology
  1981-1887 - Key technology program activities
  1990 - SPS commercialization
  2000 - SPS initial operational capability

- 25% mass contingency—15% cost contingency
- Management and integration costs at 5%
- Costs to be in 1979 dollars
- Add construction operations (RCI/O&M) to CIPS

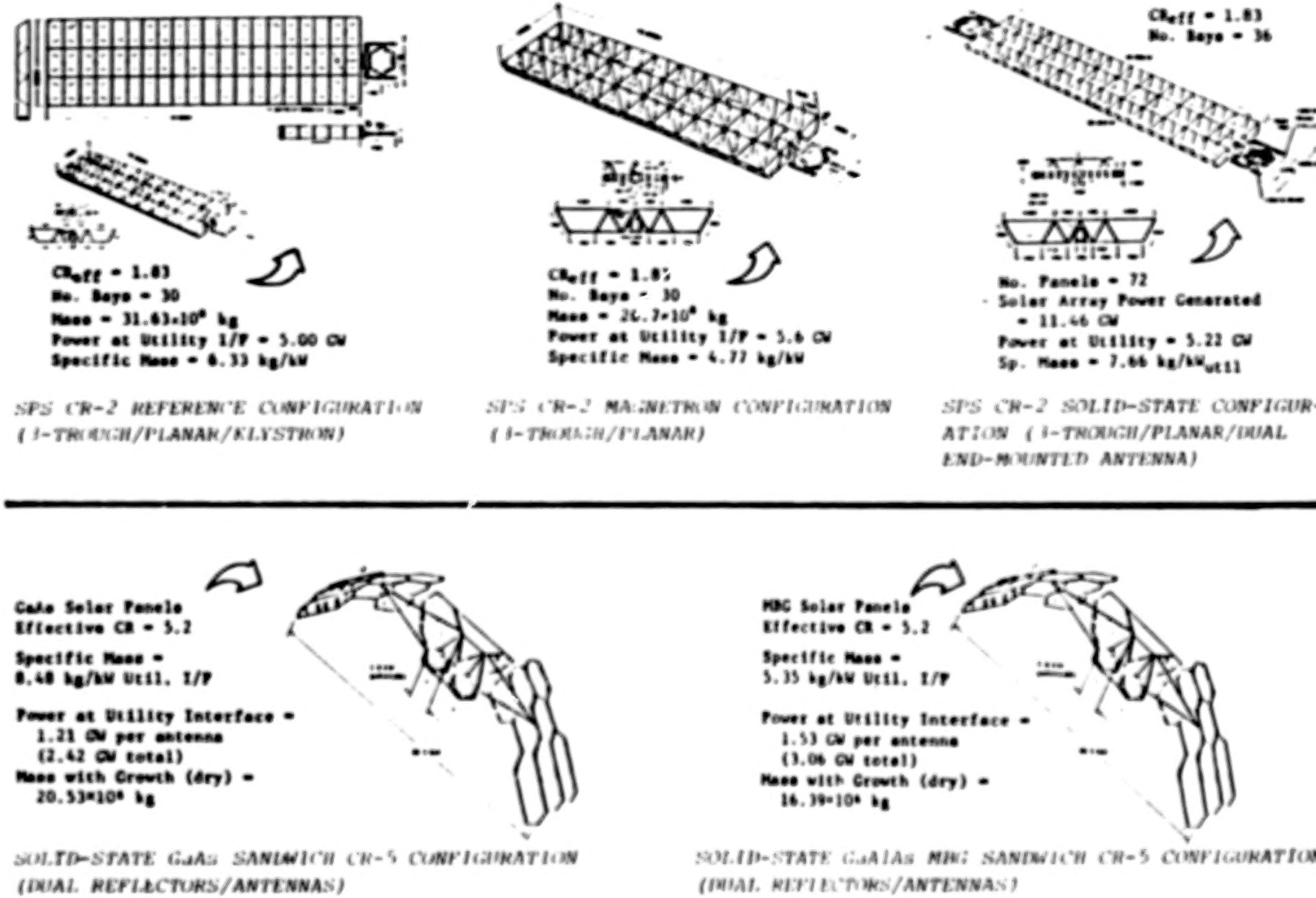

Figure 4.4-1. Rockwell SPS Concepts—1980

Table 4.4-1. SPS Work Breakdown Structure

HARDWARE AND ACTIVITIES	PROGRAM PHASE			
	DDT&E	THEORETICAL FIRST SPS	SPS INVESTMENT PER SATELLITE	OPERATIONS
1.0 SATELLITE POWER SYSTEM				
1.1 SATELLITE				
1.1.1 ENERGY CONVERSION				
1.1.2 POWER TRANSMISSION				
1.1.3 INFORMATION MANAGEMENT & CONTROL				
1.1.4 ATTITUDE CONTROL AND STATIONKEEPING				
1.1.5 COMMUNICATIONS				
1.1.6 INTERFACE (ENERGY CONVERSION/ POWER TRANSMISSION)				
1.1.7 SYSTEMS TEST				
1.1.8 GSE				
1.1.9 PILOT PLANT				
1.2 SPACE CONSTRUCTION AND SUPPORT				
1.2.1 CONSTRUCTION FACILITIES				
1.2.2 LOGISTICS SUPPORT FACILITIES				
1.2.3 O&M SUPPORT FACILITIES				
1.3 TRANSPORTATION				
1.3.1 SPS VTO/HL HLLV				
1.3.2 COTV				
1.3.3 STS PLV				
1.3.4 POTV				
1.3.5 PM				
1.3.6 IOTV				
1.3.7 GROUND SUPPORT FACILITIES				
1.4 GROUND RECEIVING STATION				
1.4.1 SITE AND FACILITIES				
1.4.2 RECTENNA SUPPORT STRUCTURE				
1.4.3 POWER COLLECTION				
1.4.4 CONTROL				
1.4.5 GRID INTERFACE				
1.4.6 OPERATIONS				
1.5 MANAGEMENT AND INTEGRATION				

4.4.3 SPS COST RELATIONSHIPS

Summarized SPS costs are shown in Figure 4.4-2 for the Rockwell reference SPS planar/klystron concept. This figure illustrates the level of costs expected for major elements of the program as it progresses from DDT&E through fully operational phases.

The front-end DDT&E estimate of $33.6 billion consists of one-time costs associated with designing, developing, testing, and evaluation of components, subsystems, and systems required for the SPS program. It includes the development engineering testing and support necessary to translate a performance specification into a design. This covers technology advancement/verification and ground-based exploratory development plus program plan definitions, detail drawings for system hardware fabrication, system integration, and required space and ground tests along with needed ground support systems.

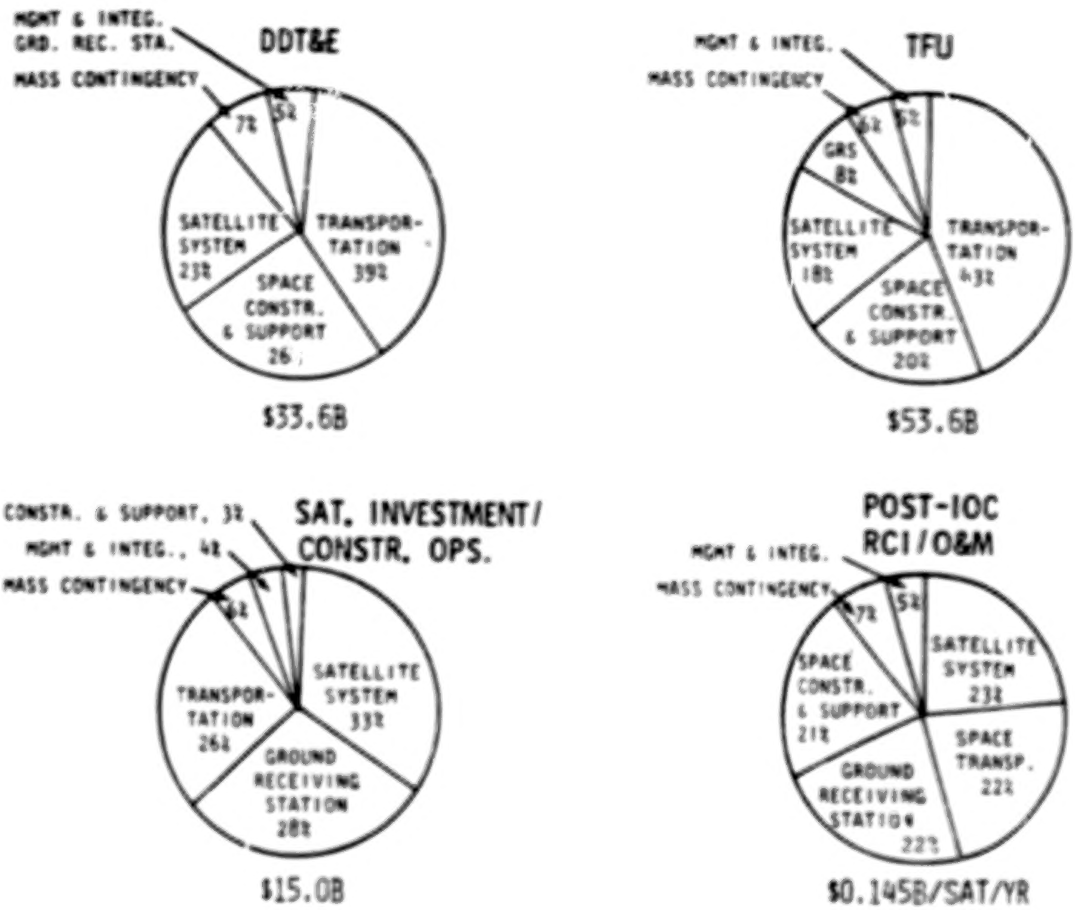

Figure 4.4-2. Rockwell Reference Planar/Klystron Concept (1980 Exhibit D)

Over 85% of DDT&E costs fall within the areas of space transportation, space construction and support, and the satellite, where the SPS VTO/HL HLLV accounts for over three quarters of the transportation DDT&E cost. The space construction DDT&E projection is about equally distributed over facilities and equipment of the space construction base (SCB) and LEO base. System ground test hardware/operations represent some 60% of the satellite DDT&E cost estimate.

The $15.0 billion average investment cost for an SPS covers a single satellite and rectenna, plus a prorated share of the transportation, space construction, and supporting system costs. Design and cost-effectiveness studies of satellite systems (power transmission subarrays, power distribution and control, and secondary structures) have resulted in generally lower costs and less mass to orbit. Transportation optimized studies on the use of space vehicles and the need for lower transfer of mass to orbit during satellite construction have reduced overall costs. However, some impact was created on investment costs by the ground rule to now include cost estimates of fleet and construction equipment replacement/maintenance. These costs have always been considered, but were previously included within an operational cost category.

Another comparison is shown in Figure 4.4-3, where DDT&E and theoretical first-unit (TFU) cost estimates were combined to illustrate significant elements of cost associated with the first SPS. It should be noted that space transportation system and ground facilities are double those of the satellite system or the space construction/support elements.

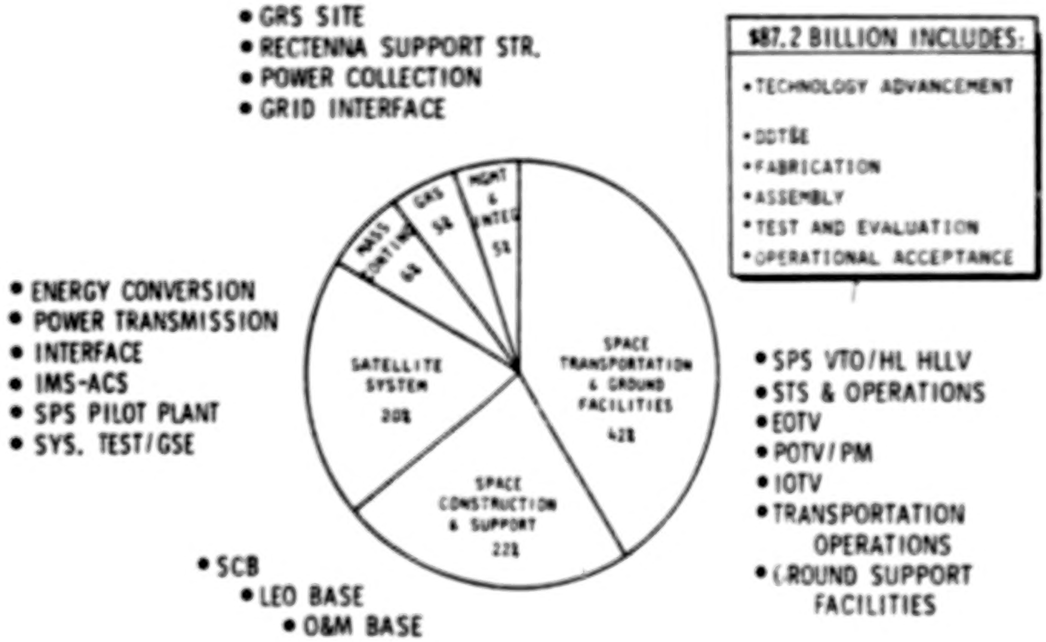

Figure 4.4-3. Total Cost of the First Operational SPS

Costs of the first SPS not only include the cost of technology advancement and DDT&E plus the system hardware and facilities, they also include the cost of all systems and components needed to construct, test, and verify the first SPS. This covers the cost of (1) a transportation system that will have a lifetime capability of building more than one satellite, (2) a space construction equipment/base designed to service an entire SPS option, (3) ground construction equipment to build many rectenna receiving stations, and (4) the factories and equipment for further system development.

Three cost categories comprise the SPS program. Table 4.4-2 on the Rockwell SPS reference concept identifies the investment per satellite and the average costs of replacement capital/maintenance (RCI/O&M) during the construction period. Space transportation is the main item of construction RCI/O&M and is nearly the same as the transportation investment cost per SPS. This same equivalency can be noted for the space construction element.

4.4.4 SPS CONCEPT COMPARISONS

Summarized cost estimates for five of the SPS concepts studied during the past year are grouped by concept within each of the SPS program phases (see Table 4.4-3). This comparison indicates that projected levels of expenditure for DDT&E, the first unit, and the average investment per SPS favor the magnetron concept of the planar family. These differences are negligible for the reflector/sandwich design, but lean toward the GaAs concept from an investment standpoint.

Table 4.4-2. Rockwell SPS Reference Concept (1980)

COST CATEGORY	1979 DOLLARS (BILLIONS)						
	TOTAL	SATELLITE	SPACE CONSTR.	SPACE TRANSP.	GROUND STATION	MGMT. & INTEGR.	MASS CONTING.
DDT&E	33.6	7.8	8.6	13.1	0.1	1.5	2.5
INVESTMENT PER SATELLITE	12.7	5.0	0.2	2.0	4.2	0.5	0.8
CONSTRUCTION RCI/O&M	2.3	-	0.2	1.9	0.05	0.1	0.05
TOTAL	15.0	5.0	0.4	3.9	4.25	0.6	0.85
SPS OPERATIONS RCI/O&M ($/SAT/YR)	0.145	0.034	0.031	0.032	0.032	0.006	0.010

Table 4.4-3. SPS Concept Comparisons

SPS CONCEPT	SPS OPTION QUAN.	1979 DOLLARS (BILLIONS)					
		DDT&E	TFU	INVESTMENT PER SATELLITE	CONSTRUCTION OPERATIONS (RCI/O&M)	POST-IOC OPERATIONS ($/SAT/YR)	INSTALLATION COST $/kW
REFERENCE UPDATE GaAs PLANAR/KLYSTRON (5.00 GW_{UTIL})	60	33.6	53.6	12.7	2.3	0.14	$3000
				15.0			
THREE-TROUGH GaAs PLANAR-MAGNETRON (5.60 GW_{UTIL})	54	31.7	52.0	11.8	2.2	0.13	$2500
				14.0			
THREE-TROUGH GaAs PLANAR-SOLID STATE (5.22 GW_{UTIL})	58	35.0	56.0	15.0	2.8	0.14	$3[illegible]
				17.8			
DUAL REFLECTORS GaAs-SANDWICH (2.42 GW_{UTIL})	125	32.7	57.3	7.4	1.5	0.08	$3680
				8.9			
DUAL REFLECTORS MBG-SANDWICH (3.06 GW_{UTIL})	98	32.8	55.7	7.8	1.3	0.08	$2975
				9.1			

As basic total system costs are less meaningful within themselves, a comparison of SPS power levels at the utility interface against capital investment cost can provide a normalizing relationship. The bar chart in Figure 4.4-4 identifies $/kW installation costs and compares the $2500/kW for a magnetron concept with the nearly $3000/kW for the sandwich configuration. The uppermost part of the bars highlight that portion of the costs for replacement capital and operations/maintenance during the construction (or pre-IOC) period of the SPS program. In all cases, the majority of these costs are attributable to the transportation system.

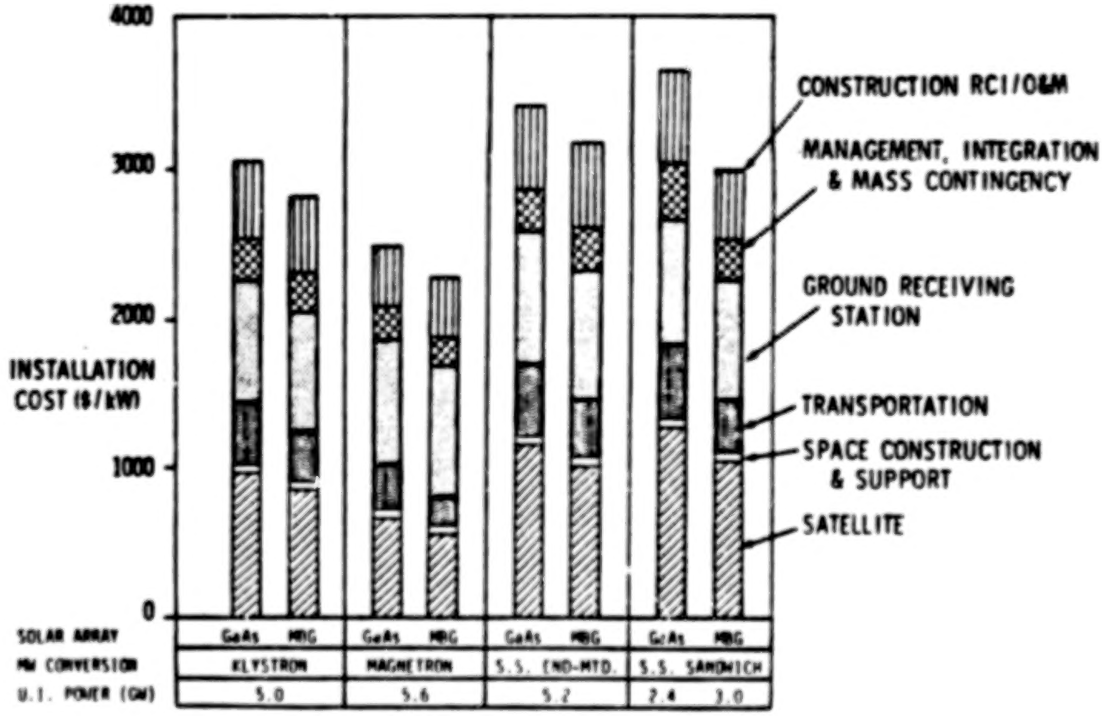

Figure 4.4-4. Installation Cost Comparisons

Prior analyses have indicated several advantages of the magnetron concept as to installation cost and projected mills per kilowatt-hour at the utility interface. On this basis, and to obtain more insight as to the areas of high cost, the SPS planar magnetron configuration was analyzed at system levels to identify high-cost items (potential cost drivers). About 90% of the SPS dollar value in each phase of the program is acknowledge in the matrix of Table 4.4-4. Close review shows that certain program elements are consistently significant in each phase. This suggests the importance of careful study/analyses for optimum definition, development, and fabrication throughout the program. Among the more prominant items are solar blankets, power transmission subarrays, space construction facilities, SPS VTO/HL HLLV, rectenna support structure, and power collection systems.

Table 4.4-4. Potential Cost Drivers—Magnetron Concept

MAJOR PROGRAM ELEMENT	DDT&E	TFU	AVG. INVEST/SAT	POST-RCI/O&M
	$31.68B	$52.00B	$14.05B	$0.127B/SAT-YR
PERCENTAGE OF TOTAL	96%	94%	87%	95%
SATELLITE SYSTEM (1.1)	18% • GROUND SYSTEM TEST EQUIPMENT & OPNS • ANT. MAINT. EQUIPMENT • PILOT PLANT	13% • PILOT PLANT • SOLAR BLANKETS • MAGNETRON SUBARRAYS	19% • SOLAR BLANKETS • MAGNETRON SUBARRAYS	8% • PWR. DISTR. & COND. • SOLAR BLANKETS
SPACE CONSTRUCTION AND SUPPORT (1.2)	27% • SPACE CONSTRUCTION BASE • LEO BASE	18% • SPACE CONSTRUCTION BASE • O&M FACILITIES	3% • SPACE CONSTRUCTION BASE	24% • O&M SUPPORT
TRANSPORTATION/ GROUND FACILITIES (1.3)	40% • SPS VTO/HL HLLV • GROUND FACILITIES • PERSONNEL LAUNCH VEHICLE	44% • SPS VTO/HL HLLV • COTV (ELECTRIC) • GROUND FACILITIES • STS	24% • SPS VTO/HL HLLV • COTV (ELECTRIC)	26% • SPS VTO/HL HLLV • GROUND FACILITIES • COTV (ELECTRIC)
GROUND RECEIVING STATION (1.4)		9% • RECTENNA SUPPORT STRUCTURE • POWER COLLECTION	32% • RECTENNA SUPPORT STRUCTURE • POWER COLLECTION	27% • GRS OPERATIONS
MANAGEMENT/INTEGRA- AND MASS CONTINGENCY (1.5,1.6)	11% • MANAGEMENT AND INTEGRATION • MASS CONTINGENCY	10% • MANAGEMENT AND INTEGRATION • MASS CONTINGENCY	9% • MANAGEMENT AND INTEGRATION • MASS CONTINGENCY	10% • MANAGEMENT AND INTEGRATION • MASS CONTINGENCY

4.4.5 SPS COMPARATIVE INVESTMENT ASSESSMENT

Comparative analysis based on the systems definition of a Rockwell SPS planar/magnetron concept offers potentially the lowest installation cost in $/kW and mills/kW-hr at the utility interface. RCI/O&M costs before the satellite's IOC are an important part of the overall investment obligation and appear to now make the transportation system a more dominant SPS investment cost element.

During this contracted study, methods of operational and maintenance support to the satellite were defined and evaluated to determine a cost-effective approach of servicing the satellite during its lifetime. A concept of centralized O&M facilities, using mobile maintenance bases to reach the satellites as required, appears as a viable method of satisfying O&M requirements. This approach was defined and used in arriving at costs for all concepts.

5.0 SUPPORTING RESEARCH AND TECHNOLOGY REPORTS

Critical technology areas have been identified for most of the subsystems and disciplines within the scope of activities covering the SPS program. Supporting research and technology (SRT) planning packages of early analysis/ experimental research and development tasks all have a focus on the R&D period, 1981-1986.

The next sections of this report contain descriptions of tasks, schedule phasing, and cost projections associated with each R&D technology area—solar conversion, electric power distribution processing and power management, power transmission and reception, structures/controls and materials, space operations, and space transportation. Establishment of firm designs, performance levels, development requirements, cost/efficiency trades, and system environmental acceptability all depend on early verification of achievable characteristics for the confirmation of projected costs.

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SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TECHNOLOGY TITLE: **SYSTEMS DEFINITION**

TECHNICAL SUMMARY

The objectives of systems definition and planning is to provide for the integration of subsystems and systems into a preferred SPS concept and to assess candidate alternative concepts responsive to the results of environmental, societal, and comparative assessment impacts on system design. This includes the consideration of economic viability and the benefits of other emerging technologies to the SPS concept. It encompasses development plans for the orderly transition of research and development plans for the orderly transition of research and development to SPS commercialization.

The essential function to be performed in the near term is to translate technology improvements and/or test and analysis results into system/program-level technology considerations with defined cost, performance schedule, and resource requirements of both ground and space flight programs.

TASK SUMMARY

The objective of this project is to complete a conceptual-level definition of an SPS preferred concept that incorporates the results of reference system updates/refinements; societal, environmental, comparative assessment; technology projects; and evaluation/comparison of alternative concepts.

Alternate Concept Assessment

The objective of this task is to analyze and evaluate several known and any other alternative SPS concepts for comparison with the reference system in terms of design and performance characteristics, technology requirements, and costs.

Technology Impacts on System Design

The objective of this system engineering project is to coordinate and establish subsystem test requirements, maintain cognizance over technology investigations, analyze evaluate, and incorporate technology program results as appropriate. This activity will provide essential functions of translating technology improvements and/or test and analysis results into system-level considerations of cost, performance, and natural resource requirements.

Environmental, Societal, and Comparative Assessment Impacts on System Design

The objective of this project is to maintain cognizance of SPS environmental/societal, and comparative assessment projects conducted by the DOE; and periodically determine and evaluate the impact of findings on SPS performance and cost characteristics; and suggest and investigate mitigating design or operational approaches where necessary.

System Analysis and Planning

The objective of this project is to define the necessary analyses, ground tests, and space flight projects that would be conducted during SPS technology development and verification phases, and to then determine resources and sequences required for SPS implementation as it progresses toward operational capability.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: SYSTEM INTEGRATION

TECHNOLOGY REQUIREMENTS

The objective of this project is to complete a conceptual-level definition of an SPS preferred concept that incorporates the results of reference system updates/refinements; societal, environmental, comparative assessment; technology projects; and evaluation/comparison of alternative concepts.

TECHNICAL APPROACH

Several concept definition studies have been completed or are now in progress to integrate system and subsystem performances and design parameters that have identified initial SPS reference concepts.

This project will integrate the results of reference system updates, DOE assessment projects, NASA technology projects, and alternative system comparisons to synthesize preferred concept selection criteria that will be formulated for comparing alternative concepts. This interaction requires that reference system specification be established for a most effective development of technology. Potential tasks include:

- Establish SPS performance parameters for subsystem design/development objectives.
- Employ environmental, societal, and economic concerns and benefits within SPS design, development, and operational requirements.
- Incorporate advanced energy conversion and structural/control desigh definitions for SPS concept integration.
- Develop power management system conceptual design studies for definition of space and ground systems.
- Identify advanced engine performance criteria and vehicle elements for transportation system optimization.
- Utilize microwave system options and preliminary design definitions.
- Incorporate design requirements for maximum benefit of space and ground segments of the microwave system.
- Integrate space construction definition and SPS design characteristics for optimum results and efficiencies.
- Embody technology impacts and conduct program assessments.
- Identify cost and programmatic aspects of program development and update SPS models, estimates, and scenarios.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ALTERNATE CONCEPT ASSESSMENT

TECHNOLOGY REQUIREMENTS

The objective of this task is to analyze and evaluate several known and any other alternative SPS concepts for comparison with the reference system in terms of design and performance characteristics, technology requirements, and costs.

TECHNICAL APPROACH

Available design, performance, and cost data will be obtained for each alternate concept. Where such data are not available, estimates and design assumptions will be ma-e to permit equitable comparisons with the reference system. Potential alternatives include magnetron microwave transmission, laser power transmission systems, solid-state microwave "sandwich" concept, thermal cycle, and other potential concepts. Tasks include:

- Identification and assessment of candidate concepts at comparative subsystem levels.
- Select promising concepts and define configurations.
- Revise/update configurational characteristics for reference system integration.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: TECHNOLOGY IMPACTS ON SYSTEM DESIGN

TECHNOLOGY REQUIREMENTS

The objective of this system engineering project is to coordinate and establish subsystem test requirements, maintain cognizance over technology investigations, analyze, evaluate, and incorporate technology program results as appropriate. This activity will provide essential functions such as translating technology improvements and/or test and analysis results into system-level considerations of cost, performance, and natural resource requirements.

TECHNICAL APPROACH

Appropriate contacts with cognizant government and industry personnel will be established to periodically evaluate/revise subsystem/component characteristics as indicated by test and/or analytical results of the technology projects. In support of the reference system project, revised subsystem/component performance, mass, cost, and material resource requirements will be produced.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ENVIRONMENTAL, SOCIETAL, AND COMPARATIVE ASSESSMENT IMPACTS ON SYSTEM DESIGN

TECHNOLOGY REQUIREMENTS

The objective of this project is to maintain cognizance of SPS environmental/societal, and comparative assessment projects conducted by the DOE; and periodically determine and evaluate the impact of findings on SPS performance and cost characteristics; and suggest the investigation of mitigating design or operational approaches where necessary.

TECHNICAL APPROACH

Appropriate contacts will be established with cognizant government, industrial and/or academic personnel to obtain first-hand test and/or analytical information having an effect on engineering aspects of SPS performance, cost, or social acceptance. Tasks include consideration of:

- Societal Impact. Monitor effect on studies of resources, institutional involvement, international relationship, and social aspects for system implications.
- Environmental Impacts. Conduct interfaces with responsible organizations to maintain cognizance over system implications resulting from such items as microwave effects and radiation.
- Comparative Assessment Impacts. Maintain cognizance over DOE projects on the assessment of SPS performance, cost, and schedule parameters.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: SYSTEM ANALYSIS AND PLANNING

TECHNOLOGY REQUIREMENTS

The objective of this project is to define necessary analyses, ground tests, and space flight projects that would be conducted during SPS technology development and verification phases and to then determine resources and sequences required for SPS implementation as it progresses toward operational capability.

TECHNICAL APPROACH

The initial task in this project is to develop preliminary test and verification requirements based on interim results and reports from the reference system update/refinement, technology investigations, and DOE assessment projects. Conceptual (Phase A) definition studies will then be conducted to parametrically determine cost-effective test projects. Following review and DOE/NASA concurrence, selected projects will be defined in more detail and a technology development and verification program plan will be completed. Subsequent actions will be taken to define future program phases. Subtasks include:

- Test Requirements. Define requirements to validate system concepts and the integration of two or more systems. This includes ground and space tests for individual system combinations as well as that of the integrated proof-of-concept test verification activity.
- Definition of Projects. Maintain orderly completion of Phase A and Phase B studies of SPS reference/preferred concepts.
- Program Planning and Analysis. Prepare program plans and development sequences for the evolutionary transition from research and technology development to Phase C/D SPS commercialization.

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	4.4.4 SPS Concept Comparisons	4-28	1/F14
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5.0	SUPPORTING RESEARCH AND TECHNOLOGY REPORTS	5-1	1/G6

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN	TASK TITLE: SYSTEM DEFINITION							
MILESTONE SCHEDULE	FY →	1981	1982	1983	1984	1985	1986	1987
SYSTEM INTEGRATION								
ALTERNATE CONCEPT ASSESSMENT								
TECHNOLOGY IMPACTS ON SYSTEM DESIGN								
ENVIRONMENTAL, SOCIETAL, AND COMPARATIVE IMPACTS ON SYSTEM DESIGN								
SYSTEM ANALYSIS AND PLANNING								

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TECHNOLOGY TITLE: **SPS SOLAR CONVERSION TECHNOLOGY**

TECHNICAL SUMMARY

The objective of this program is to identify, research and develop the component and subsystem technologies for an advanced solar energy conversion subsystem to support future SPS design and tradeoff studies. A GaAs photovoltaic subsystem has the potential of low weight, high efficiency, higher resistance to ionized radiation levels, and the ability to operate with concentrators under high temperature with a minimum loss in performance.

The attainment of a set of certain design parameters for the conversion system is critical to assuring SPS cost viability, and the proof of feasibility of attaining these design parameters is necessary.

It is recommended that investigations be continued of advanced concepts that offer potential of significant advances in performance, mass, and/or cost of the photovoltaic energy conversion system over the "reference" concepts and designs. New system studies should be conducted to re-evaluate concentration ratio and evaluate new developments to provide an even more optimistic perspective for SPS for additional technological "breathing room" for the concept.

TASK SUMMARY

Basic Solar Cell Research and Development. The objective of this program is to develop the technology for 20% efficiency, thin film GaAs solar cells on suitable substrates, and establish manufacturing processes, equipment, and physical plant requirements for SPS solar cell production.

GaAs Solar Cell Qualification Program. Under this program the problems associated with qualification of the candidate solar cell are identified, and recommendations made. Although outside the scope of GBED, it will be necessary to space operate the solar cells to determine the effects of plasma on operation in a thermal vacuum and radiation environment. The program can probably be best achieved from the Shuttle orbiter and will also include confirmation of the cell annealing temperature and recovery process.

Solar Array Demonstration Program (Including Array). The objective of this program is to demonstrate that solar cells with reflectors at concentration ratio 2 will achieve power levels of 280 watts/m^2 at panel masses of 0.252 kg/m^2. 1000 volts dc strings will be investigated to examine plasma interaction. Test designs will establish if these tests can be conducted during ground testing, or whether on-orbit testing will be necessary. Additional investigations will include temperature, concentration ratio, radiation, and annealing impacts. Capabilities will be measured against cost goals of \$67/m^2 of blanket and \$2.5/m^2 of reflector.

Accelerated, 30 Year Lifetime Testing. Under this program the stability of components such as solar cell and reflector to assure a 30 year life will be established by simulating the geosynchronous orbit radiation intensities. Computer simulations will be used to provide modeling and analytical techniques. Technology will be defined and developed to harden against radiation degradation.

Manufacturing Processes Analysis and Cost Evaluation. The objective of this program is to perform an indepth evaluation of solar cell mass production manufacturing method, and to select and demonstrate an appropriate production method in keeping widh SPS objectives of \$67/m² for the blanket array and \$2.5/m² for the reflectors.

Multi-Bandgap Thin Film Solar Cell Development. Thin film multi-bandgap technology offers the promise of 35% AMO cell efficiency and this program is designed to establish a procedure by which they will be developed. Modeling techniques will be applied for predicting the performance of, and selecting cells. The tolerance of the cell efficiencies to low and high thermal radiation, annealing methods and background radiation will be established.

Alternate Advanced Concept Evaluation. Recent development of a low efficiency very inexpensive amorphous silicon solar cell has occurred. The cell is also sensitive to thermal and nuclear radiation. Alternative methods such as spectrum splitting and higher concentration will be investigated to assure cognizance over potential technical breakthroughs in the development period and recognition of their impact on SPS design.

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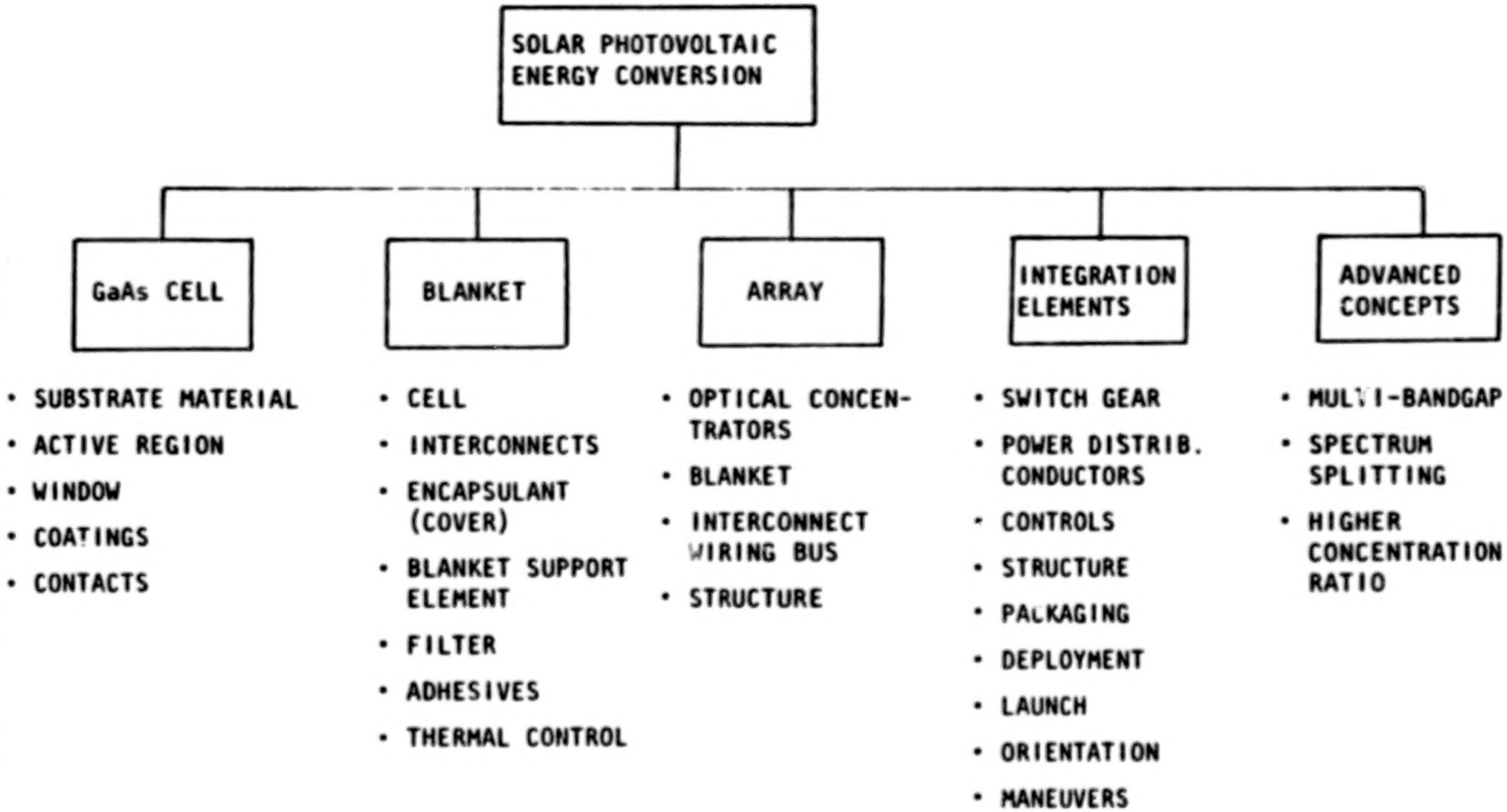

SPS SOLAR PHOTOVOLTAIC ENERGY CONVERSION TECHNOLOGY

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN	TASK TITLE: SPS SOLAR CONVERSION TECHNOLOGY						
MILESTONE SCHEDULE FY →	1981	1982	1983	1984	1985	1986	1987
GaAs SOLAR CELL RESEARCH AND DEVELOPMENT						◇	
GaAs SOLAR CELL QUALIFICATION PROGRAM						◇	
SOLAR CELL DEMONSTRATION PROGRAM						◇	
ACCELERATED SOLAR CELL TESTS						◇	
MANUFACTURING PROCESSES AND COST EVALUATION						◇	
MULTI-BANDGAP THIN FILM SOLAR CELL DEVELOPMENT						◇	
ALTERNATIVE ADVANCED CONCEPT EVALUATION						◇	

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: BASIC SOLAR CELL RESEARCH AND DEVELOPMENT

TECHNOLOGY REQUIREMENTS

A solar power satellite capable of delivering 5 GW of power to the utility on the ground will require an array output of approximately 9.76 GW at the end of life. Utilizing the GaAs type cell will result in a solar blanket area of approximately 30.6 km^2 which is considerably less area than if Si type cells were used. The GaAs cell offers the potential of high efficiency, low weight, reduced deployment area, high efficiency at elevated operating temperatures which permits concentrators to be used for obtaining concentration ratios up to 5 to 7, and the GaAs cell is more resistant to the space radiation environment compared to Si cells.

STATE OF THE ART

GaAs solar cells have been fabricated through LPE growth processes to 200-300 μm cell thickness, and at AMO solar cell efficiency of over 18% have been measured in the laboratory. These cells do have better temperature coefficient, radiation hardening and higher cell efficiencies than silicon cells.

TECHNICAL OBJECTIVES

The objective of this effort are:

- Demonstrate and develop the technology for fabricating 16% efficiency thin-film ($\leq$10 μm thick) GaAs solar cells on suitable substrate in 1983 and 18% efficiency cells in 1986.
- Develop and apply rigorous analytical modeling techniques for predicting the performance of GaAs thin film cells.
- Conduct basic research to understand radiation damage and annealing effects of various GaAs solar cell configurations and feasibility of low-temperature annealing to remove radiation damage.
- Develop and improve feedstock materials for cell fabrication processes (such as ribbon growth) and cell structures.
- Design preliminary manufacturing processes, equipment, and physical plant requirements for eventual SPS cell production.

TECHNICAL APPROACH

- Investigate and develop high efficiency thin film GaAs solar cell structures based on MO-CVD or other suitable mass production fabrication methods.

- Model, design, and performance analyze thin-film GaAs cells. Demonstrate 18% efficiency (AMO), $\leq$ 10 μm thick, $\geq$ 10 cm^2, inexpensive substrate capable of meeting SPS cost and weight goals [16% (AMO) within 2 years]. Develop suitable contacts that use non-noble metals and are weldable. Develop lab-type pilot line production for life testing.

- Conduct basic research and determine thin film GaAs solar cell radiation damage and annealing properties.

- Develop and improve (feedstock) materials with required properties, reduce costs and high volume production potential.

- Perform paper design and projection of manufacturing processes (strawman process sequence), production equipment, and physical plant requirements for large-scale manufacture of GaAs thin film cells for SPS. Evaluate barriers to production within SPS cost goals.

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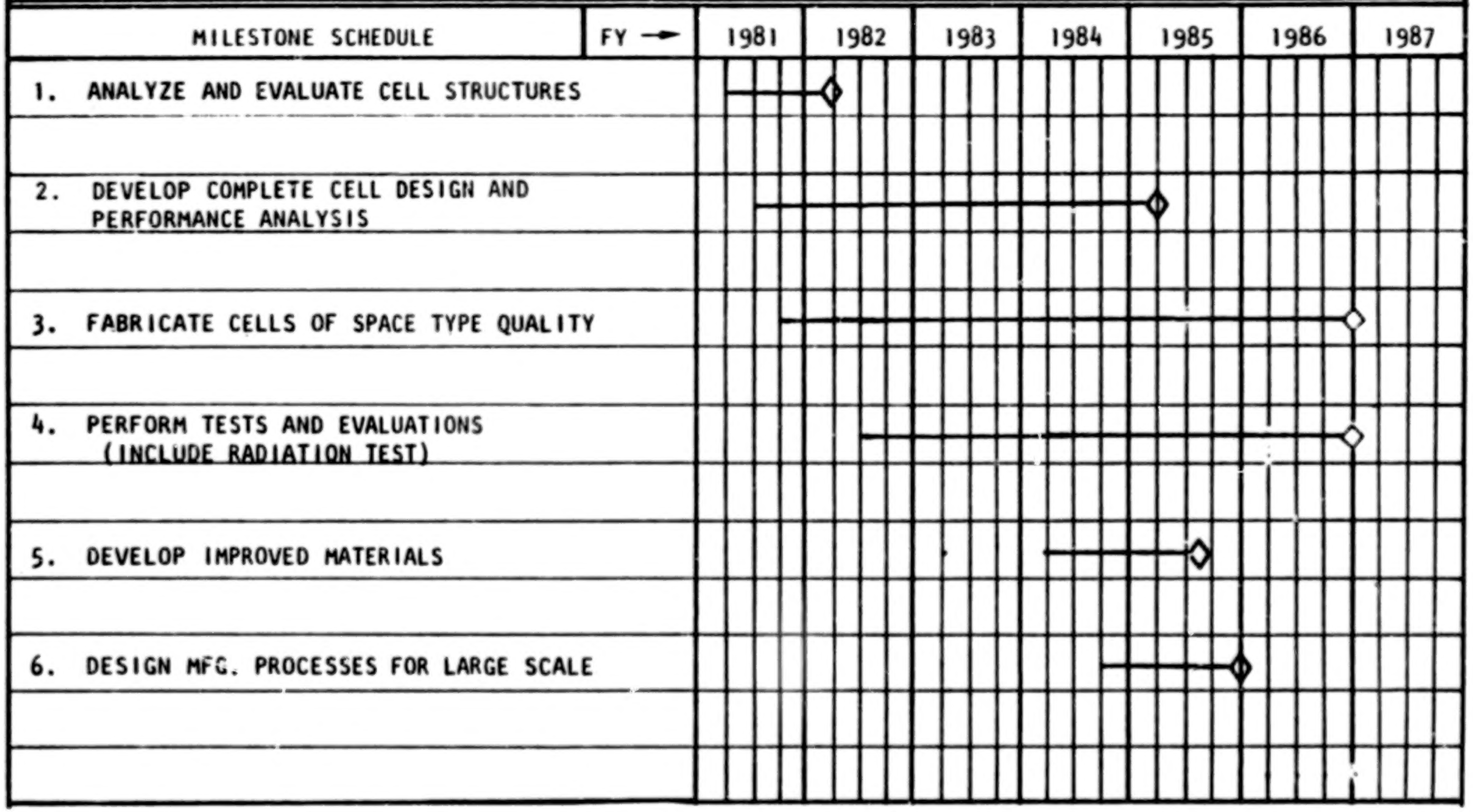
SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: GaAs SOLAR CELL RESEARCH AND DEVELOPMENT



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: GaAs SOLAR CELL QUALIFICATION PROGRAM

TECHNOLOGY REQUIREMENT

High-efficiency, thin-film GaAs solar cell with active cell thickness 5-10 μm under orbital operating conditions is a critical performance parameter that, in turn, affects essentially all other design aspects of the SPS.

STATE OF THE ART

HESP GaAs solar cells fabricated through LPE growth process has demonstrated 16% (AMO).

TECHNICAL OBJECTIVES

- Ensure the thin-film GaAs cell efficiency and producibility
- Qualify the thin-film GaAs cell for various space radiation environment temperature cycling. Demonstrate EOL 16.2% (AMO) for 30-year equivalent GEO environment.
- Confirm the cell annealing temperature and recovery process.

TECHNICAL APPROACH

- To qualify the solar cell for the SPS program (demonstrate space-worthy design), the following tests should be performed:

  Thermal optical properties test

  Temperature dependence test

  Ultraviolet irradiation

  Electronic irradiation

  Storage test

  Temperature cycling test

  Solar cell contact integrity test

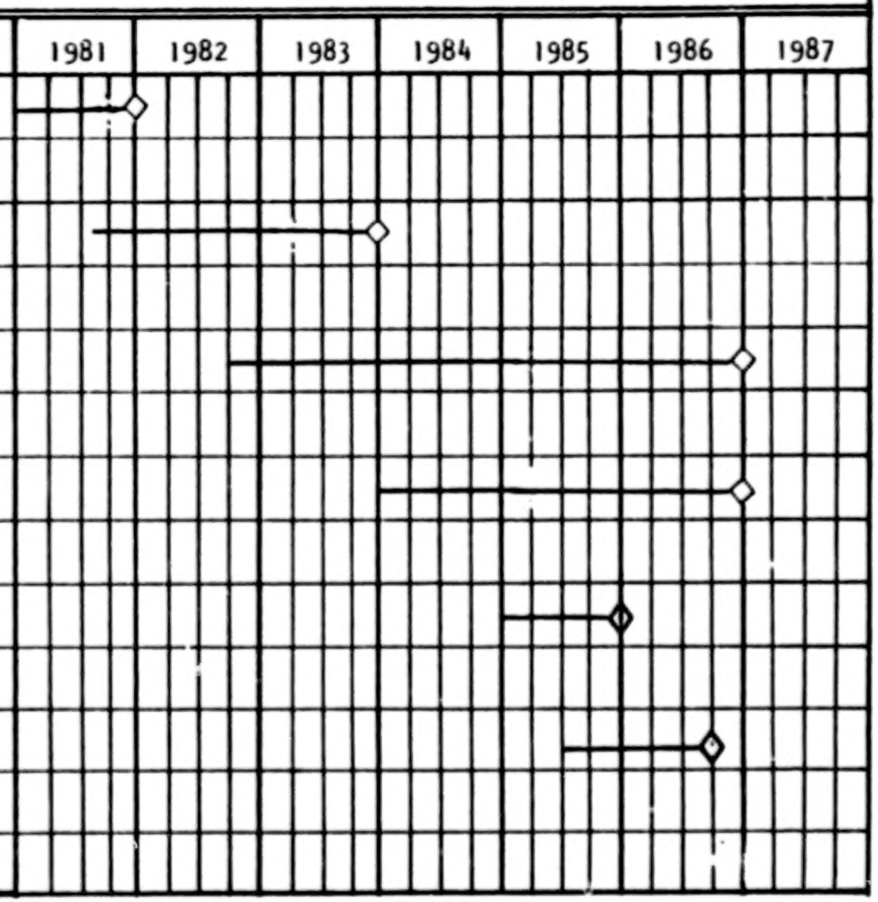
  Orbital flight data

  Cell annealing and recovery rate test

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN	TASK TITLE: GaAs SOLAR CELL QUALIFICATION PROGRAM

MILESTONE SCHEDULE FY →

1. DETERMINE THE EXPERIMENTS & EQUIPMENTS
2. DESIGN & FABRICATE BASIC COMPONENTS FOR TESTS EXPERIMENT
3. CONDUCT SOLAR CELL QUALIFICATION TESTS & EVALUATE RESULTS
4. RECOMMENDATION & MODIFICATION
5. DEFINE ON ORBIT TEST PROGRAM
6. FLIGHT TEST



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: **SOLAR ARRAY DEMONSTRATION PROGRAM**

TECHNOLOGY REQUIREMENT

A 5 gigawatts GaAs satellite power systems (SPS) requires the solar array platform dimensions 4.2x16 km and satellite mass 34×10^6 kg. Also high voltage (-45.7 kV) solar arrays will be required to obtain a practical SPS design. Gigawatts power system and high voltage analytical design data for solar arrays are non-existent for space application. A comparable solar array demonstration program is required in order to obtain the basic technology data for use in the design and sizing studies for the SPS.

STATE OF THE ART

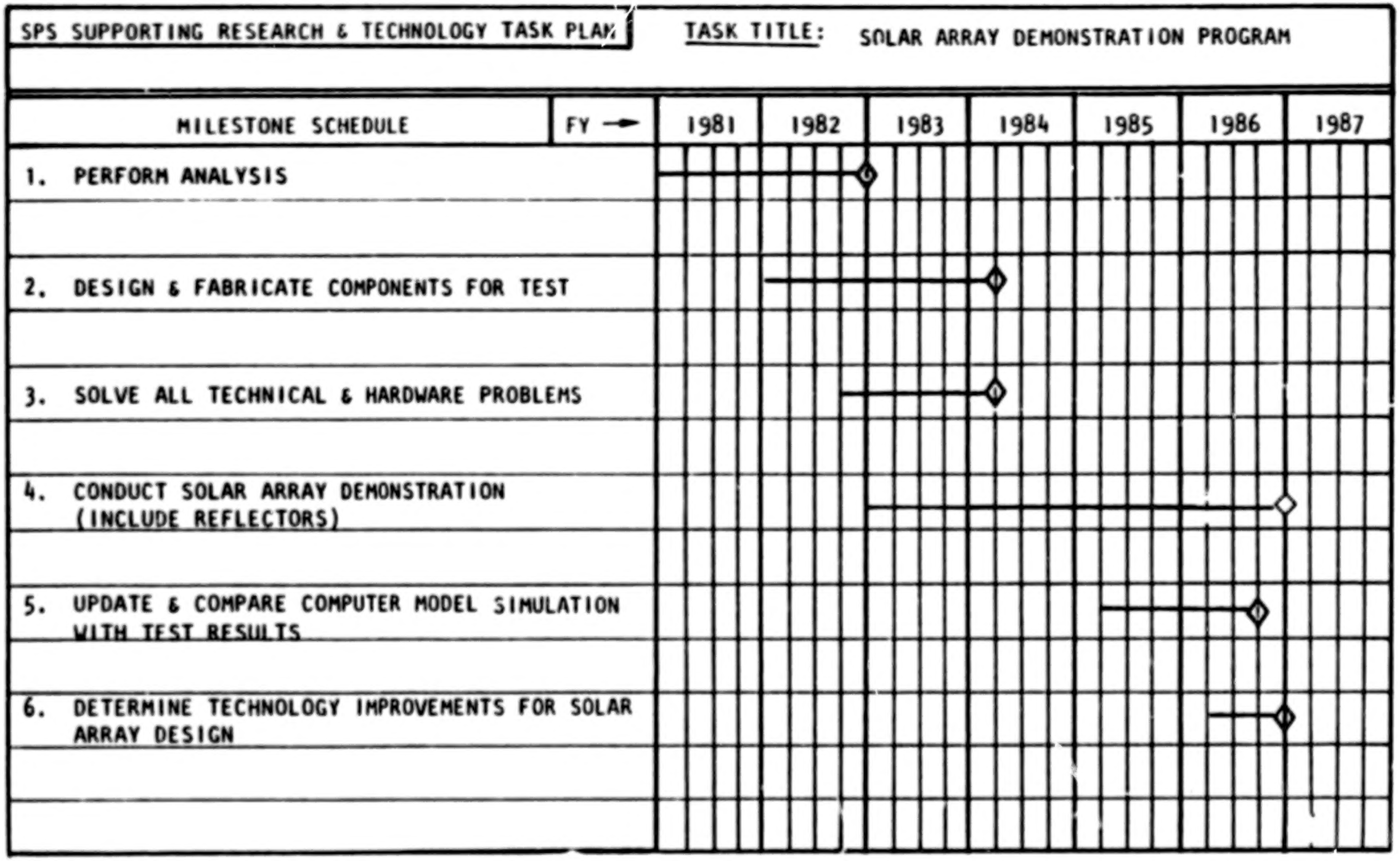
SEPS, PEP and PS type multi-kW solar array utilizing the conventional silicon solar cells with 100-200 volts panel voltage output has been demonstrated on the ground.

TECHNICAL OBJECTIVES

- Demonstrate GaAs solar cells with CR=2 can achieve power output 280 W/m^2 and panel mass 0.315 kg/m^2 which is 80% of the SPS goal.
- Demonstrate at least 1000 V dc strings panel voltage output and examine high voltage plasma interactions
- Demonstrate solar array capable of surviving annealing temperature.
- Demonstrate by cost studies that solar array cost capable of meeting SPS cost goals of $\$67/m^2$ for blanket and $\$2.5/m^2$ for reflector.

TECHNICAL APPROACH

- Examine high solar cell string voltage impacting on plasma interactions.
- Examine the status of art of the power conversion distribution technology.
- Design the CR=2, SPS GaAs solar array with proper annealing temperature to meet 80% of SPS power requirement and mass goal.
- Perform blanket integration—development of encapsulation techniques, interconnects and submodule bus designs, bonding, and integrated techniques for production of submodules.
- Do a system-level re-evaluation of concentration ratio to achieve more optimistic perspective for SPS.
- Perform dynamic analysis of the array. Conduct launch vehicle integration study.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: SOLAR ARRAY DEMONSTRATION PROGRAM
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
1. PERFORM ANALYSIS
2. DESIGN & FABRICATE COMPONENTS FOR TEST
3. SOLVE ALL TECHNICAL & HARDWARE PROBLEMS
4. CONDUCT SOLAR ARRAY DEMONSTRATION (INCLUDE REFLECTORS)
5. UPDATE & COMPARE COMPUTER MODEL SIMULATION WITH TEST RESULTS
6. DETERMINE TECHNOLOGY IMPROVEMENTS FOR SOLAR ARRAY DESIGN

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ACCELERATED SOLAR CELL TESTS (30-YR LIFETIME PROGRAM)

TECHNOLOGY REQUIREMENT

The stability and reliability of the SPS solar array, reflector, etc., for the 30-year missions, have great impact on the design and size of the SPS system.

STATE OF THE ART

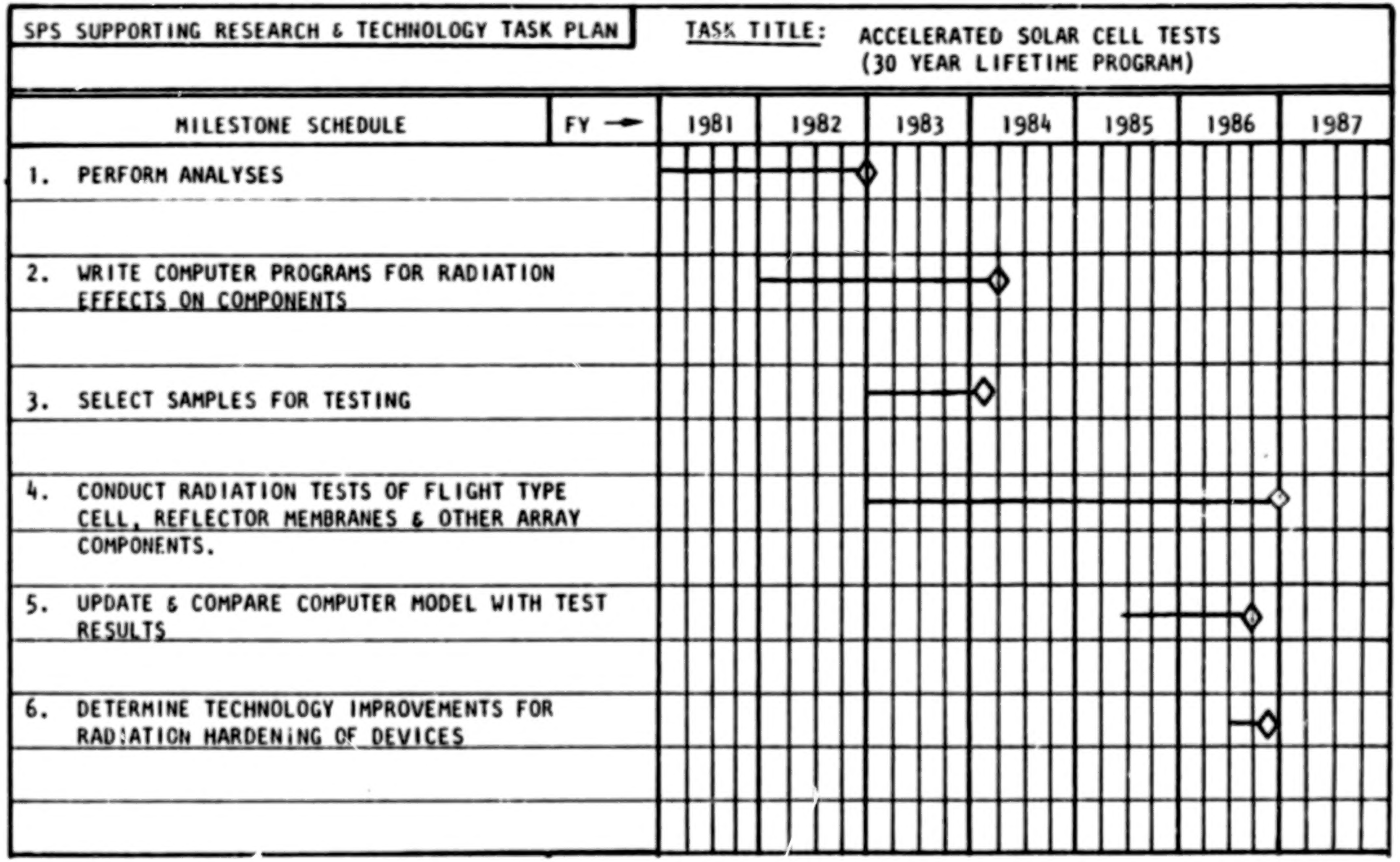
The information about reliability and stability of solar cell, reflector, and other solar array components is unknown.

TECHNICAL OBJECTIVES

- Ensure the 30-yr lifetime performance stability and reliability of GaAs solar cells, interconnects, covers, and supporting elements in operational environment.
- Determine the degradation damage of solar array and reflector.

TECHNICAL APPROACH

- Define, develop, and conduct an accelerated testing program for 30-year GEO radiation, vacuum, and temperature. [Stability testing to be initiated after a cell efficiency of 16% (AMO) has been established.]
- Fabricate test articles.
- Perform thermal-cycle, radiation, Shuttle launching tests.
- Develop and apply rigorous analytical modeling techniques for predicting the performance of the solar array panel and reflectors. Research physical degradation mechanisms. Define 30-year environment.
- Retest the modified test articles and compare to the computer modeling simulation results.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: ACCELERATED SOLAR CELL TESTS (30 YEAR LIFETIME PROGRAM)
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
1. PERFORM ANALYSES
2. WRITE COMPUTER PROGRAMS FOR RADIATION EFFECTS ON COMPONENTS
3. SELECT SAMPLES FOR TESTING
4. CONDUCT RADIATION TESTS OF FLIGHT TYPE CELL, REFLECTOR MEMBRANES & OTHER ARRAY COMPONENTS.
5. UPDATE & COMPARE COMPUTER MODEL WITH TEST RESULTS
6. DETERMINE TECHNOLOGY IMPROVEMENTS FOR RADIATION HARDENING OF DEVICES

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MANUFACTURING PROCESSES ANALYSIS AND COST EVALUATION

TECHNOLOGY REQUIREMENT

A solar power satellite capable of delivering 5 GW of power to the utility on the ground will require an array output of approximately 9.76 GW at the end of life. One of the major components that have a significant impact on the SPS weight and cost is the design and performance of the GaAs solar cell. The development and refinement of the mass production fabrication process for the manufacture of GaAs cells has the potential for high production rates for the cells. The manufacturing process has to be developed in order to obtain high performance cells with high manufacturing yields and low unit cost which are required to make the SPS economically viable with advanced power plants.

STATE OF THE ART

- MO-CVD solar cell fabrication method has been demonstrated in the laboratory and proved to be an excellent candidate for mass production.
- Rockwell has fabricated GaAs heterface solar cell with 20% AMO efficiency on small cell area (0.0272 cm^2) by MO-CVD method in the laboratory.

TECHNICAL OBJECTIVES

- Analyze the manufacturing processes and design improved techniques and equipment that will result in the manufacture of high efficiency GaAs cells.
- Fabricate and test cells to demonstrate the improved CVD processes or other suitable mass production fabrication methods.
- Cost evaluation the optimum manufacturing methods to achieve the SPS cost goals of \$67/m for array blanket and \$2.5/m for reflectors.

TECHNICAL APPROACH

- The process variables, tolerances and the equipment size have to be defined.
- Investigate and define gallium recovery techniques and recovery rates.
- Establish production yields, process times, mfg. costs and plant size which are necessary to determine production rates.
- Define facility requirements and cell costs.
- Analyze the gallium cycle for recycling, minimizing losses and reduction in gallium content for cell performance.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MANUFACTURING PROCESSES ANALYSIS AND COST EVALUATION

MILESTONE SCHEDULE	FY →	1981	1982	1983	1984	1985	1986	1987
1. DEFINE PROCESS VARIABLES								
2. DETERMINE EQUIPMENT SIZE & PRODUCTION								
3. DEFINE FACILITY REQUIREMENTS								
4. INVESTIGATE THE GALLIUM PROCESS FOR RECOVERY AND RECYCLING								
5. DEMONSTRATE MASS PRODUCTION PROCESS (SUCH AS CVD) CONTROL AND TECHNOLOGY								
6. COST EVALUATION								

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MULTI-BANDGAP THIN FILM SOLAR CELL DEVELOPMENT PROGRAM

TECHNOLOGY REQUIREMENT

Thin film multi-bandgap solar cell offers over 25% AMO cell efficiency with potential 35% cell efficiency which depends on the selection of junctions and materials. Higher than 20% single junction GaAs conversion efficiency cell will reduce significantly the size, mass, and cost from the present SPS design.

STATE OF THE ART

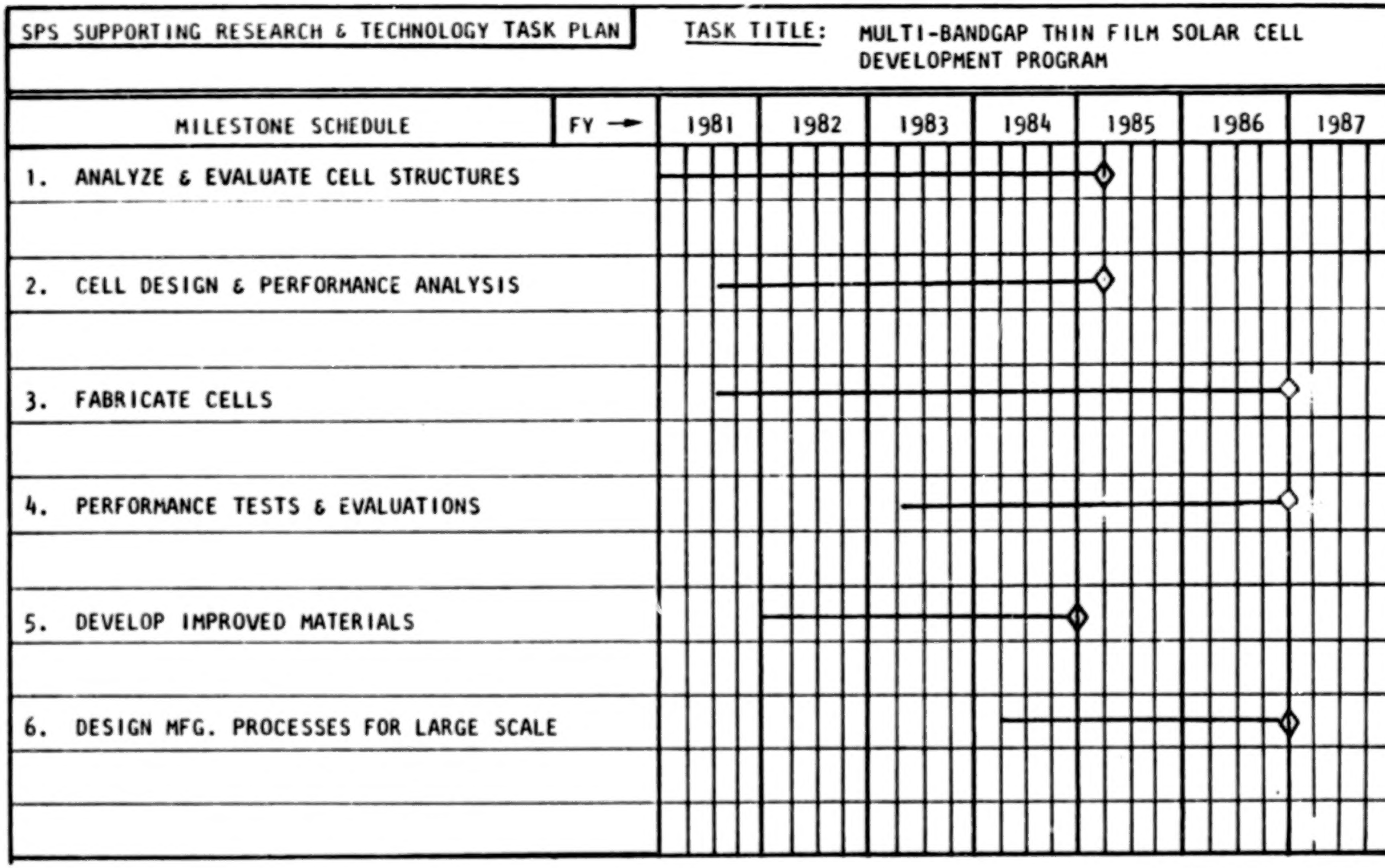
GaAlAs/GaAs dual junction solar cell has demonstrated cell open-circuit voltage around 2.2 V in the laboratory. Due to the materials interface problem, short-circuit current is lower than conventional Si, GaAs single junction cells.

TECHNICAL OBJECTIVES

- Demonstrate and develop the technology for fabricating over 25% AMO efficiency thin film multi-bandgap solar cell.
- Develop and apply rigorous analytical modeling techniques for predicting the performance of multi-bandgap thin film cells.
- Determine and select the optimum semiconductor materials combination and numbers of junction for SPS design.
- Determine the tolerance of various multi-bandgap solar cell configurations to irradiation by charged particles and feasibility of low temperature annealing to remove radiation damage.

TECHNICAL APPROACH

- Investigate and develop high efficiency thin film multi-bandgap solar cell structures based on MO-CVD or alternative fabrication methods.
- Model, design and performance analyzes thin film multi-bandgap cells.
- Determine thin film multi-bandgap solar cell radiation damage and annealing properties
- Develop and improve (feedstock) materials with required properties, reduce costs and high volume production potential.
- Perform preliminary design and projection of manufacturing processes, production equipments for SPS mass production.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: MULTI-BANDGAP THIN FILM SOLAR CELL DEVELOPMENT PROGRAM
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
1. ANALYZE & EVALUATE CELL STRUCTURES
2. CELL DESIGN & PERFORMANCE ANALYSIS
3. FABRICATE CELLS
4. PERFORMANCE TESTS & EVALUATIONS
5. DEVELOP IMPROVED MATERIALS
6. DESIGN MFG. PROCESSES FOR LARGE SCALE

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ALTERNATIVE ADVANCED CONCEPT EVALUATION

TECHNOLOGY REQUIREMENT

Gigawatt satellite power systems have been defined which utilize GaAs or Si solar cells for energy conversion. Based on the overall SPS system and cost analysis, the concept of CR=2, GaAs and CR=1, Si photovoltaic power conversion seems to be the favorable candidate. Future technology developments having a significant positive impact on the SPS design. Other alternative photovoltaic conversion sources and advanced concept should be examined in order to enrich the SPS concept.

STATE OF THE ART

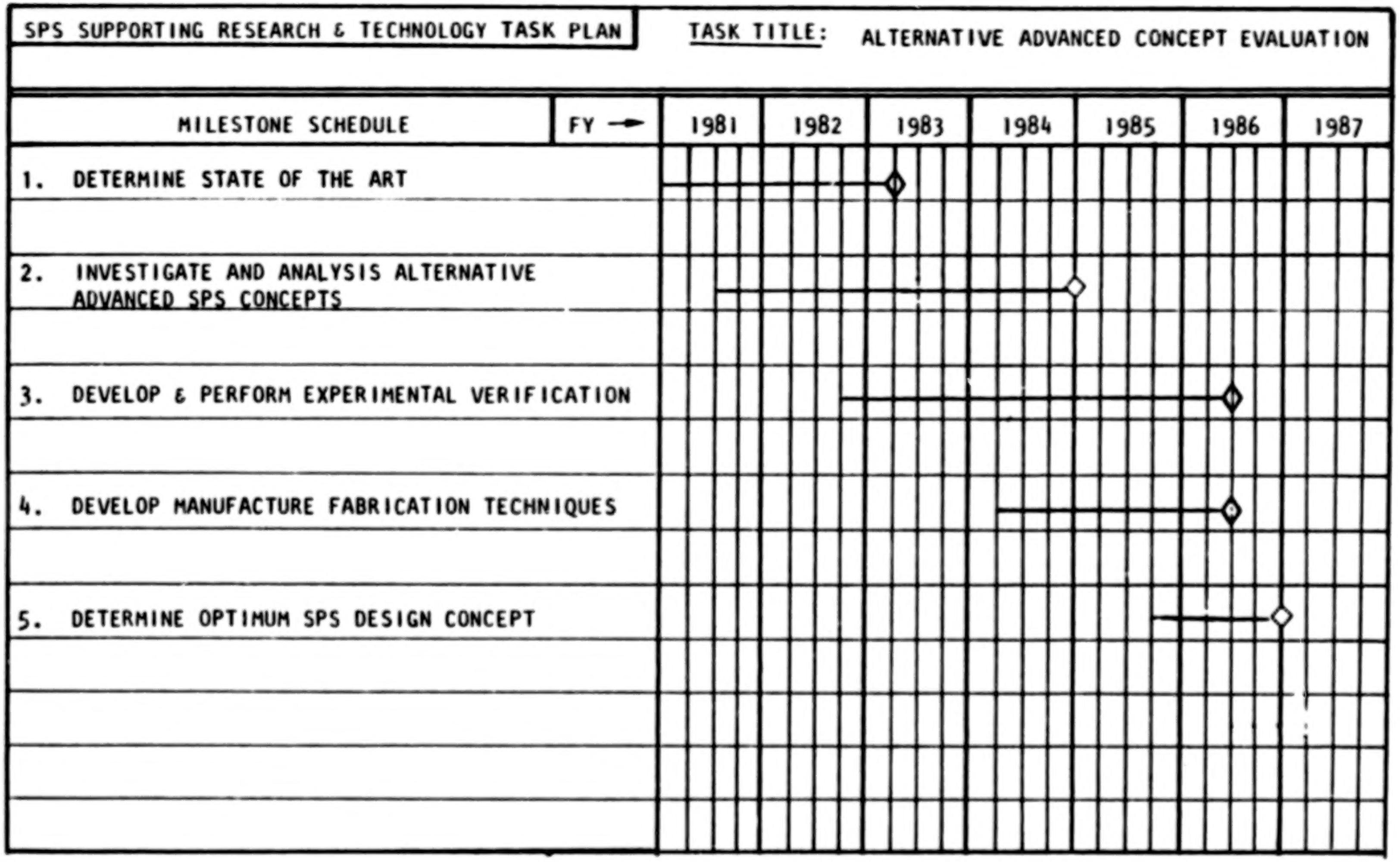
- Multi-bandgap solar cell concept
- Multi-spectral cells and spectrum splitting device concept
- High performance concentrator photovoltaic system concept
- Thermo photovoltaic cells concept

TECHNICAL OBJECTIVES

- Examine and analyze alternative advanced SPS concepts to move toward 50% goal based on system design, cost, and resources
- Perform experimental verification works of these concepts
- Develop manufacturing fabrication techniques

TECHNICAL APPROACH

- Evaluate the state of the art on future technology development
- Examine alternative advanced concept which impact on SPS design performance, cost with minimum delay and technological complication
- Examine materials resource capability
- Develop manufacturing fabrication techniques


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: ALTERNATIVE ADVANCED CONCEPT EVALUATION
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
1. DETERMINE STATE OF THE ART
2. INVESTIGATE AND ANALYSIS ALTERNATIVE ADVANCED SPS CONCEPTS
3. DEVELOP & PERFORM EXPERIMENTAL VERIFICATION
4. DEVELOP MANUFACTURE FABRICATION TECHNIQUES
5. DETERMINE OPTIMUM SPS DESIGN CONCEPT

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TECHNOLOGY TITLE: SPS ELECTRICAL POWER DISTRIBUTION PROCESSING AND POWER MANAGEMENT (PDC)

TECHNICAL SUMMARY

The primary objective of this early research is to establish technical feasibility and economic practicability for high voltage operations of the SPS. Technical feasibility will depend on the technology readiness of techniques, components, and equipment to reliably distribute, process, and interrupt hundreds of megawatts of power at tens of thousands of kilovolts. Minimum weight power processors and power conductors are required. The combined requirements of dissipating concentrated heat and preventing breakdown or arc-overs are much more severe in space than in similar high power and high voltage ground applications. The SPS power distribution and processing concepts depend upon successful realization of high power kilovolt ultra-fast protection switches.

Consideration should be given to the PDC requirements of alternatives to high voltage transmission tubes such as solid-state dc-RF converters.

TASK SUMMARY

Requirements Definition Study

Requirements definition studies should be expanded to ascertain that the weight and efficiency estimates of the proposed PDC equipment are based on requirements that are sufficiently complete so as to preclude gross errors in the predicted SPS weight and cost estimates and to ensure that the technology development effort required to bridge the gap between present and predicted SOA is properly defined and scoped.(1)(2)

Laboratory Experimentation and Feasibility Test Models

Investigations and laboratory experimentation should be carried out to demonstrate: (1) approaches for dc converters which will allow an extension of current mass projections from 0.5 kg/kW to 0.197 kg/kW, and (2) validation of a switch gear concept in terms of space application to achieve mass, efficiency, and size as required for the SPS.

Feasibility test models can be utilized to demonstrate high voltage operation, ultra-fast overload protection times, and specific masses. These models can provide verification of scaling relationships (weight, frequency, voltage, and power level), and data for preliminary design of SPS hardware.

Power Devices Development

Power electronic devices form the building blocks for switch gear and dc/ac converters and inverters, and as such are critical to high-performance

(1) AC power distribution should be carried on as an option until the economic practicality of high power, high voltage, fast response dc transmitter tube protection has been established.

(2) Consideration should be given to the PDC requirements of alternatives to high voltage transmission tubes such as solid-state dc-RF converters.

systems like the SPS. SPS will require new development in areas of transformers, inductors, capacitors, diodes, and SCR's.

Power Transmission Development

SPS requires transmission of extremely large current (kiloamps) at potentials of 50 kV over distances of tens of kilometers. Therefore, developments are necessary for practical transmission in these areas: conductor joining techniques, supports (insulators and standoffs), surface treatment for heat transfer, equipment/transmission line connectors. Without improvements in mass, transmission efficiency, and arc protection, the SPS will not meet its goals of technical and economic viability.

Rings and Brush Materials Development

There is a need to develop ring and brush materials that can be operated at high contact temperatures (~200°C). Also, brush materials capable of higher current densities (>7.5 A/cm^2) are needed. Consideration must be given to the problem of current distribution when multiple brushes are used on the same ring carrying very high currents.

Additional definition of the flex cable configuration is required. The mechanical properties of this system must be determined (fatigue of large-diameter mechanical interactions, etc.).

Study of Plasma Effects and Laboratory Tests

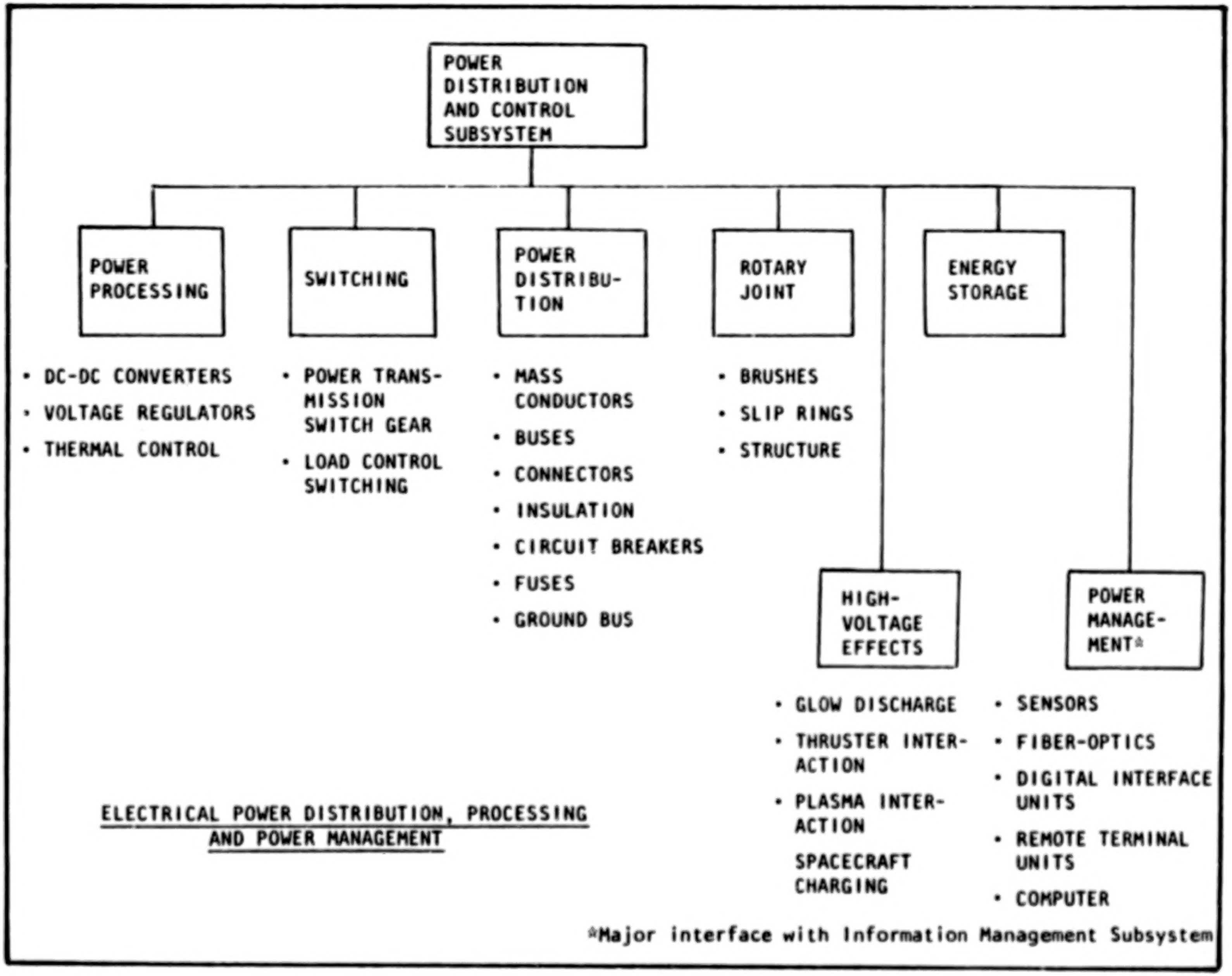
The geostationary orbit plasma environment presents special hazards to spacecraft designers because of the presence of dense, high-temperature plasma associated with the plasma sheet. Plasma sheet electrons may charge up the satellite to high voltage (of the order of 10 kV). These high voltages may cause breakdown (arcing), damage to components, changes to reflectivity or thermal control surfaces, and possibly shock hazards for EVA and docking activities. The investigation should include a theoretical analysis, computer modeling of the spacecraft fields, laboratory tests of some realistic arcing protection, solar cell arrays, and power distribution devices in a substorm plasma simulator and eventually flight tests.

Molten Salt Electrolyte Battery Design

The molten salt electrolyte battery should be designed for space application, cells built and completely characterized. Also of interest is the corrosion effects associated with the molten salt system. A study effort is needed to determine if a thermal energy storage/heat pipe configuration makes sense as a means for providing transmission tube heat during eclipse periods.

Power Management System Conceptual Design Studies

Power management system conceptual design studies must be conducted to scope the functions and hardware implementation. Developments are needed of the sensors operating at high voltages and of the fiber-optics for analog and digital data transfer and interfacing with high-voltage equipment. This effort must define the digital interface units and remote terminal units that are part of the various power distribution, power processing, energy storage, and thermal control equipment. This equipment needs to be integrated into a power management system.



ELECTRICAL POWER DISTRIBUTION, PROCESSING AND POWER MANAGEMENT

*Major interface with Information Management Subsystem

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN	TASK TITLE: POWER DISTRIBUTION, PROCESSING, AND POWER MANAGEMENT

MILESTONE SCHEDULE	FY →	1981	1982	1983	1984	1985	1986	1987
1. REQUIREMENTS DEFINITION STUDY								
2. LABORATORY EXPERIMENTATION AND FEASIBILITY TEST MODELS OF POWER PROCESSING								
3. POWER DEVICES DEVELOPMENT								
4. POWER TRANSMISSION DEVELOPMENT								
5. RING AND BRUSH MATERIALS DEVELOPMENT								
6. STUDY OF PLASMA EFFECTS & LABORATORY TESTS								
7. MOLTEN SALT ELECTROLYTE BATTERY DESIGN								
8. POWER MANAGEMENT SYSTEM CONCEPTUAL DESIGN STUDIES								

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: REQUIREMENTS DEFINITION STUDY

TECHNOLOGY REQUIREMENT

Steady-state operations at 42.9 kV and 208 kA at slip ring interface. Solar array output power level of 9.9 GW, 30-year operational life. Multiple voltages ranging from 40 kV to 8 kV at ~136,000 klystrons. Ground isolation, EMC, cathode-to-body voltage ripple, and tube arcing energy limiting protection requirements undefined. DC-to-dc converters at 0.199 kg/kW and 96% efficiency. Switching times of 5 μsec to 5 msec.

STATE OF THE ART

Present aerospace technology limited to 28 to 300 V dc and 25-100 kW with switching times of 20 milliseconds.

TECHNICAL OBJECTIVES

To expand and ascertain that the weight and efficiency estimates of the power processinq and protection equipment are based on requirements that are sufficiently complete so as to preclude gross errors in the predicted SPS weight and cost estimates; to ensure that the technology development effort required is properly defined and scoped.

TECHNICAL APPROACH

Investigate transmitter tube voltage and current requirements and expand current requirements definitions from SPS system definition studies. Simulate the SPS system and determine requirements regarding ground isolation, EMC, cathode-to-body voltage ripple, and tube arcing energy limiting protection as well as a closer approximation of the voltage and current requirements of the various depressed collectors of the transmitter tube. *Note: This may require laboratory development of the transmitter tube.* Perform a study to determine similar requirements for alternative solid-state transmitters and ac power distribution concepts.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN	TASK TITLE: REQUIREMENTS DEFINITION STUDY						
MILESTONE SCHEDULE FY →	1981	1982	1983	1984	1985	1986	1987
VOLTAGE AND CURRENT REQUIREMENTS OF DEPRESSED COLLECTORS							
UNDEFINED REQUIREMENTS (GRD ISOLATION, EMC, VOLTAGE RIPPLE, ETC.)							
SYSTEM RELIABILITY & EQUIPMENT RATING							
FLEX CABLE CONFIGURATION							
THERMAL STORAGE/HEAT PIPE CONFIGURATION							

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: LABORATORY EXPERIMENTATION & FEASIBILITY TEST MODELS

TECHNOLOY REQUIREMENT

Two major goals for the SPS early research are weight reduction in dc converters down to 0.197 kg/kW and validation of a switch gear concept in terms of space application to achieve weight, efficiency, and size as required for the SPS.

It is essential that load variations, transients, and faults be determined so that proper control requirements can be established to ensure continuous power transmittal to the ground station. It, therefore, becomes essential that mathematical models be developed for computer simulation to investigate load variations, transients, and fault-detection schemes. The simulation would then aid in locating critical areas where sensors could be located so that proper corrective action could be taken.

STATE OF THE ART

DC-dc converters at 1.0 to 2.0 kg/kW rated less than 100 kW

TECHNICAL OBJECTIVES

To demonstrate feasibility of predicted efficiency and specific weight. To demonstrate high voltage generation and thermal control, specific weight, and efficiency.

1. Develop mathematical models of components and loads
2. Develop overall PDS mathematical model
3. Investigate load variation effects
4. Investigate transient effects
5. Investigate fault detection (perform short-circuit analysis)
6. Investigate EMI effects and where filtering should be employed
7. Brassboard development and construction of a 10-kW dc converter to extend weight projection from 0.5 kg/kW to 0.197 kg/kW
8. Design and demonstrate brassboard switch gear to verify weight, efficiency, and size

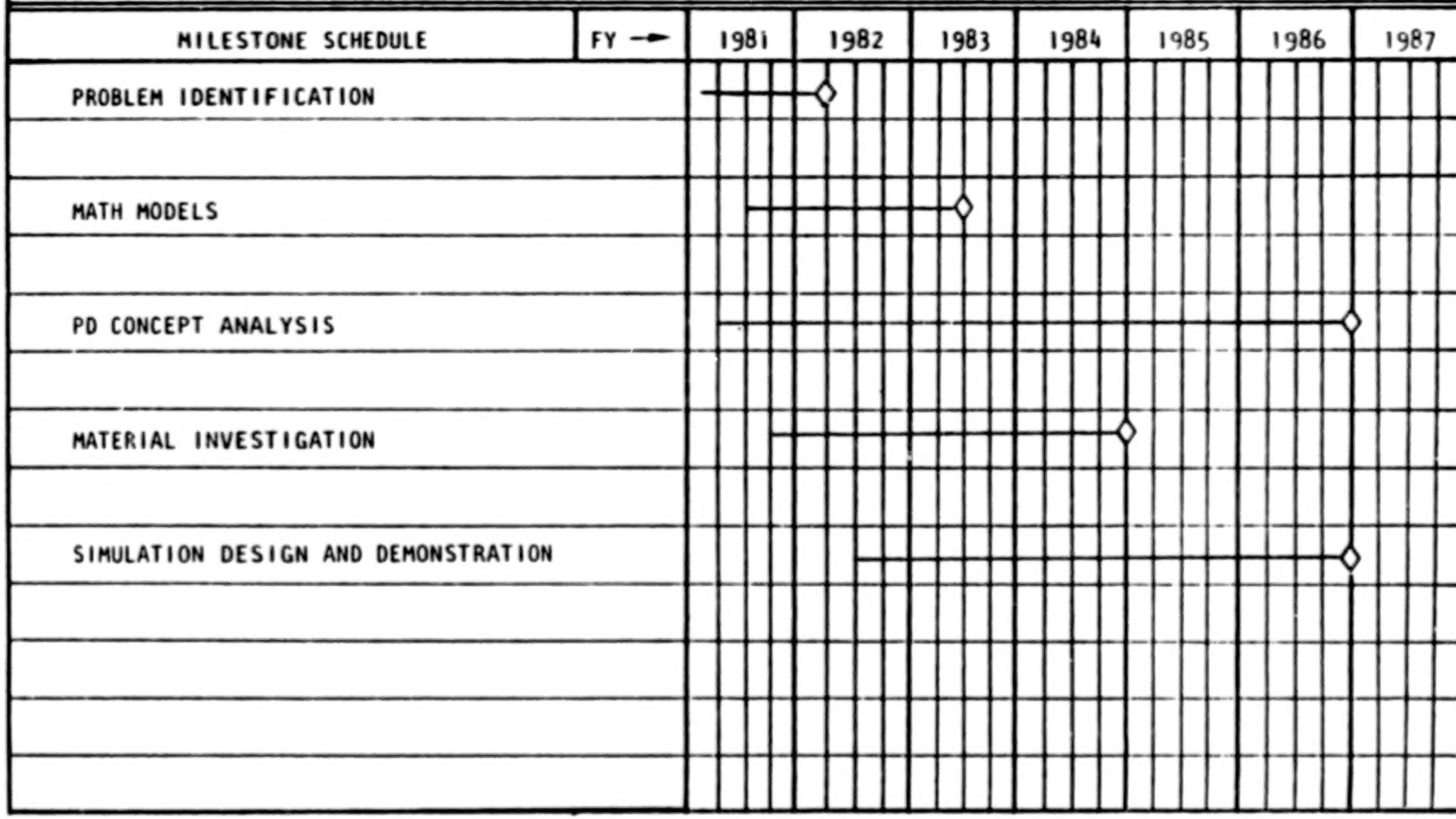
TECHNICAL APPROACH

This project will be divided into seven areas of investigation. The first will be to identify and enumerate the engineering problems which must be solved to establish the requirements and outputs of the simulation. The

second consists of building the mathematical models for the simulator and to perform a baseline configuration run. The results will be reviewed and updated where necessary. In case of update, a rerun of the baseline will be performed. The third consists of the actual study phase of PDS, presentation of the solutions, and recommendations of changes as well as additions. The fourth consists of updating the models to the latest configuration and rerunning Phase 3 to ensure that the corrections made satisfy the requirements. The fifth deals with investigation of materials and candidate mechanizations of dc converter and switch gear designs. Sixth is the design of exploratory tests; seventh is the simulation design and demonstration. Materials that will be investigated for the dc converters include lightweight, high-performance ferrites, composite hybrid materials, doping of conductors with oriented magnetic materials. In addition, investigations will be made of new semi-conductors for higher frequency, new coupling techniques and multiple-function component technology, and cooling techniques. System design simulation tests will be performed prior to design and demonstration of brassboard design.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: LABORATORY EXPERIMENTATION AND FEASIBILITY TEST MODELS



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: POWER DEVICES DEVELOPMENT

TECHNOLOGY REQUIREMENT

40 kV, ultra-high-power operation (5-10 kA)

High speed switching (5-50 msec)

99.9% efficient switch gears

94-96% dc-dc converters

STATE OF THE ART

Present technology is not available for devices operating at the SPS required power levels.

TECHNICAL OBJECTIVES

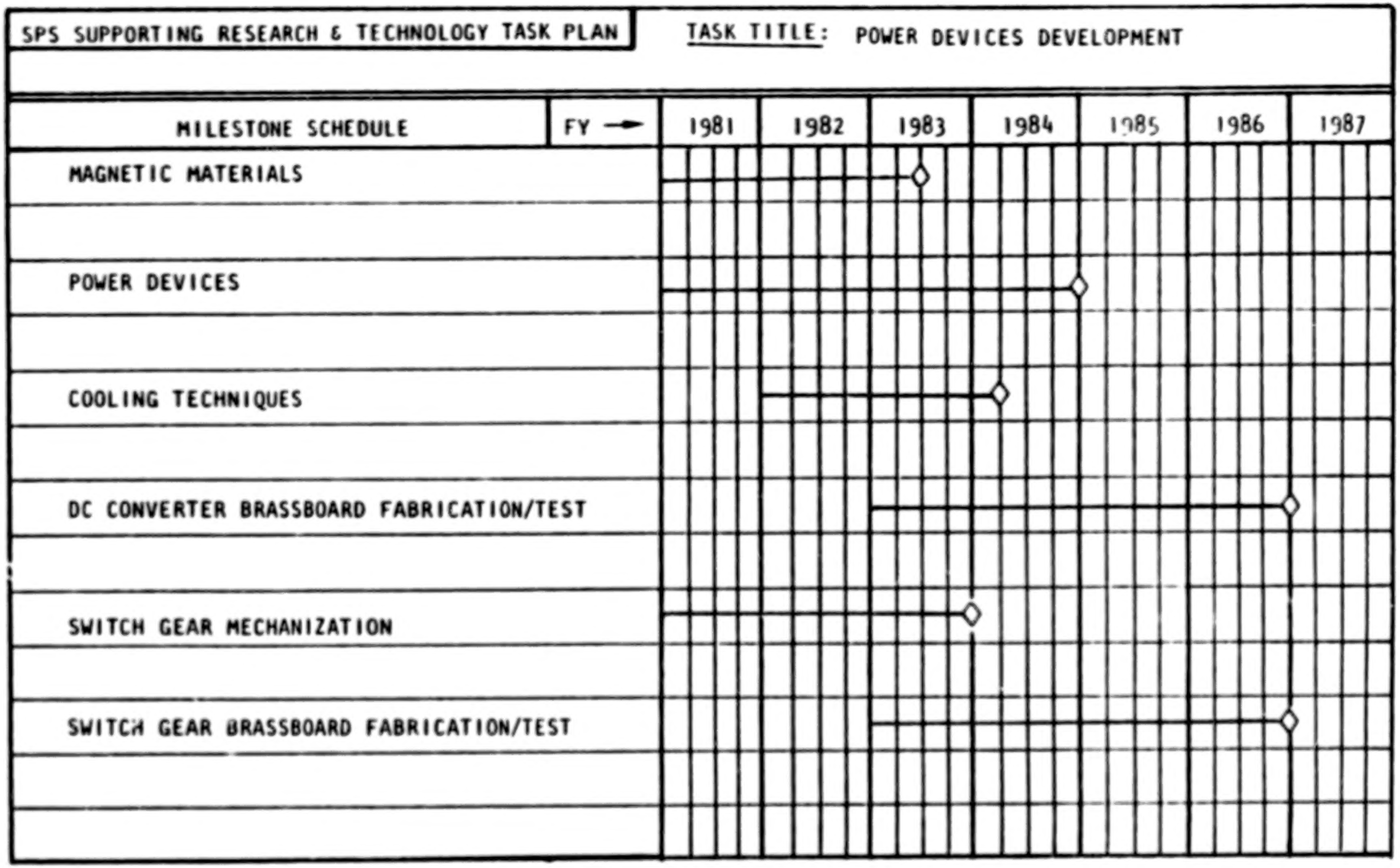
Necessary technology developments in areas of transformers, inductors, capacitors, diodes, and SCR's to advance state of the art so as to make the SPS concept technically feasible.

TECHNICAL APPROACH

The technical approach consists of two parts:

1. Investigation and development of: magnetic materials, new semiconductors and applicable devices for higher frequency and efficiency performance; new coupling techniques and multiple function component technology; and cooling techniques for power handling components.

2. Assessment of available technology (dc converter and switch gear) and definition of brassboard models. Develop, construct, and evaluate brassboards.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: POWER DEVICES DEVELOPMENT
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
MAGNETIC MATERIALS
POWER DEVICES
COOLING TECHNIQUES
DC CONVERTER BRASSBOARD FABRICATION/TEST
SWITCH GEAR MECHANIZATION
SWITCH GEAR BRASSBOARD FABRICATION/TEST

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: POWER TRANSMISSION DEVELOPMENT

TECHNOLOGY REQUIREMENT

Large current (10 kA) transmitted at potentials of 50 kV over distances of tens of kilometers.

In SPS power distribution systems, flat conductors are preferred because they exhibit better heat dissipating qualities than round conductors. However, because of the length of these conductors, they appear hard to handle; therefore, sectionalization is a necessity. The joining of these sections could alter the characteristics of the conductors; therefore, it becomes important to investigate various joining processes to determine which will produce the optimum joint.

STATE OF THE ART

Several orders of magnitude less than SPS requirements.

TECHNICAL OBJECTIVES

Evaluate weight, transmission efficiency, and arc protection for conductor joining, supports, surface treatment, and connectors. The objectives of the study are:

1. Determine most feasible joining process
2. Determine electrical and thermal characteristics (insulators and standoffs)
3. Determine mechanical characteristics and strength of joint

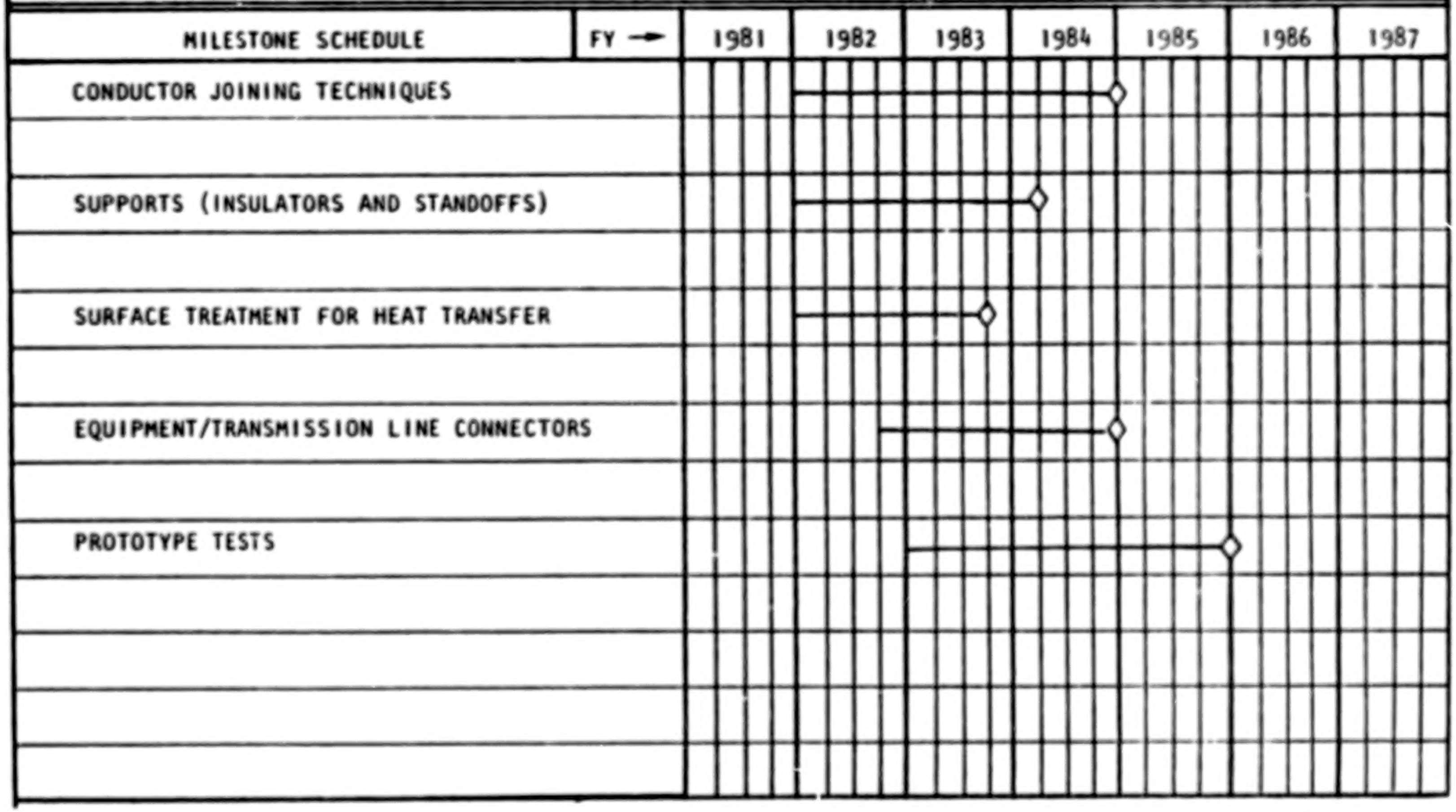
TECHNICAL APPROACH

1. Review existing flat conductor cable joining concepts. Establish SPS cable sizes and determine number of joints that may be needed.
2. Evaluate the various joining techniques such as conductive adhesives, mechanical clamping and/or weldments for potential use on the SPS.
3. Design prototype joint for potential application to the SPS and fabricate.
4. Evaluate equipment/transmission line connectors

5. Conduct tests to determine electrical and mechanical performance and strength. Assess ease of on-orbit assembly and reliability of joint.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: POWER TRANSMISSION DEVELOPMENT



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: RING AND BRUSH MATERIAL DEVELOPMENT

TECHNOLOGY REQUIREMENT

360° continuous rotation, 23° ± 10° flex joint

42.9 kV, 217,500 A transfer across rotary joint

Test and performance data of high-power slip rings

High-contact temperature (200°C)

99.9% efficiency

STATE OF THE ART

Transfer of large amounts of power at high voltages and currents through slip rings has never been performed in space—current state of the art is limited to 28-300 V, 25 kW, rotary joint dimensions of <0.5 m in diameter, and slip ring current densities of ~7.5 A/cm^2.

TECHNICAL OBJECTIVES

The objectives of the study consist of:

1. Analyzing slip ring design concepts and determining potential materials to use for the slip rings and brushes.
2. Establishing prototype model sizes, designing components, and fabricating for testing.
3. Performing laboratory test to determine electrical, mechanical, and thermal characteristics of the slip ring and brush assembly.

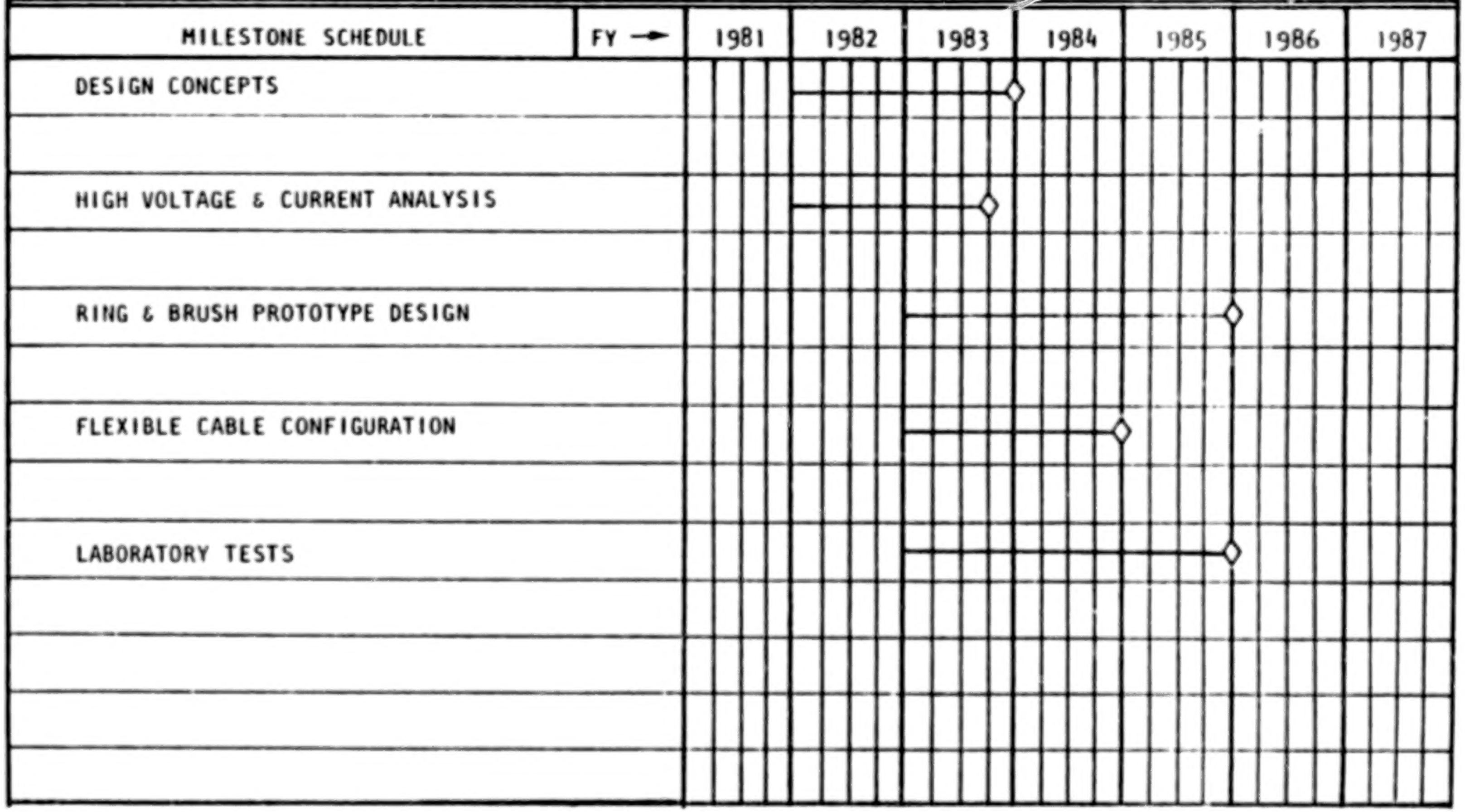
TECHNICAL APPROACH

1. Review design concepts of on-orbit slip ring brush assemblies. Determine state of the art of the technology and determine electrical, mechanical and thermal characteristics and performance of the design.
2. Analyze high-voltage/high-current slip ring requirements. Voltage drop, friction factors, wear rate, arcing, current density, brush pressure, and temperature effects are critical to the design of the slip ring brush assembly for long life and high performance.
3. Design prototype slip ring and brushes for testing.
4. Define flex cable configuration and determine mechanical properties.

5. Perform laboratory testing of prototype components and correlate test data with analytical design results.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: RING AND BRUSH MATERIAL DEVELOPMENT



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: STUDY OF PLASMA EFFECTS AND LABORATORY TESTS

TECHNOLOGY REQUIREMENT

Transmit continuous power from satellite to the ground in the presence of dense, high-temperature plasma associated with the plasma sheet. High-voltage power generation, 40 kV in GEO and >2000 V in LEO. Reliable operations, <1% loss in GEO, and <5% loss in LEO.

STATE OF THE ART

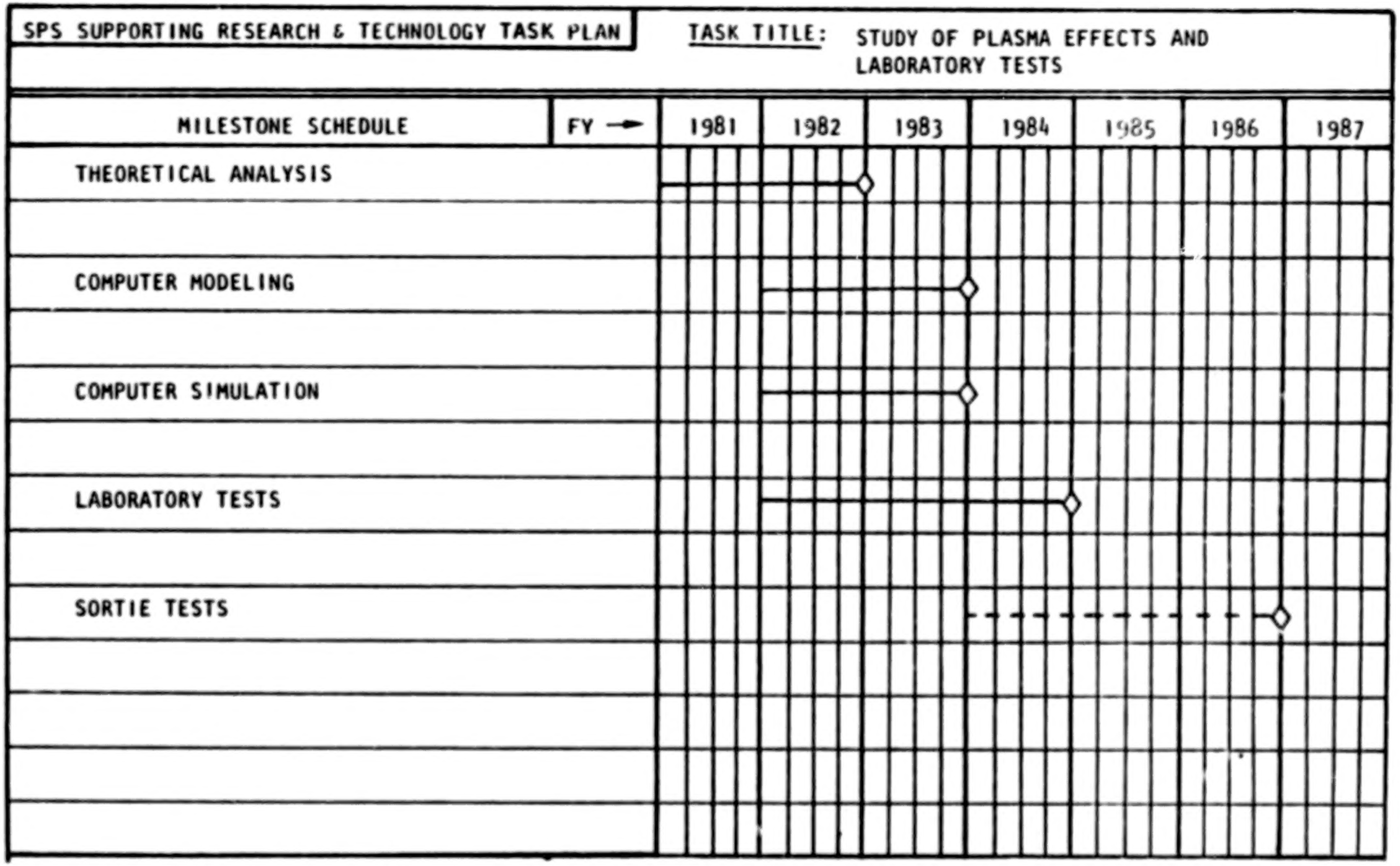
28-300V, 25 kW

TECHNICAL OBJECTIVES

1. Review existing spacecraft charge math models and determine how they could be implemented.
2. Develop spacecraft charging mathematical model for the SPS.
3. Perform coordination with simulation engineers for incorporating the spacecraft charge mathematical model into the overall PDS simulation model.

TECHNICAL APPROACH

This project will be divided into four phases. The first phase consists of a review of existing spacecraft simulation models to determine whether they could be utilized in the overall simulation model, or whether new models would have to be developed for the SPS configuration. The second phase consists of developing a suitable mathematical model to be used in conjunction with the PDS overall mathematical model. After model has been completed, simulation will be made to confirm accuracy of model. The third phase consists of interfacing with simulation engineers for incorporating the model into the overall PDS simulation model and also participate in the simulation evaluation. The last phase consists of laboratory tests of some realistic, arcing-protected solar cell arrays and power distribution devices in a substorm plasma simulator. (Eventually, flight tests in GEO and LEO will be required.)


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: STUDY OF PLASMA EFFECTS AND LABORATORY TESTS
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
THEORETICAL ANALYSIS
COMPUTER MODELING
COMPUTER SIMULATION
LABORATORY TESTS
SORTIE TESTS

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MOLTEN SALT ELECTROLYTE BATTERY DESIGN

TECHNOLOGY REQUIREMENT

Maintain essential functions during eclipse periods for restart and attitude control

Up to 40 MW-hours of energy

200 Wh/kg

80% charge efficiency

STATE OF THE ART

33 Wh/kg projected to reach 66 Wh/kg and battery cell sizes <100 AH, nickel-cadmium and silver-cadmium battery cell materials

TECHNICAL OBJECTIVES

Obtain specific energy estimates for advanced battery systems (next generation). Evaluate thermal management techniques.

TECHNICAL APPROACH

This work will consist of two parts.

1. The molten salt electrolyte battery should be designed for space application, cells built and completely characterized. Also of interest is the corrosion effects associated with the molten salt system that could seriously reduce operational life of the battery.

2. A study effort is needed to determine if a thermal energy storage/heat pipe configuration makes sense as a means for providing the heat needed by the klystron heater during non-powered periods. Should the concept appear feasible, an effort would be initiated to build and test the combined unit to prove the concept.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MOLTEN SALT ELECTROLYTE BATTERY DESIGN

MILESTONE SCHEDULE	FY → 1981	1982	1983	1984	1985	1986	1987
BATTERY DESIGN CONCEPT							
BUILD CELLS							
CHARACTERIZE CELLS							
STUDY THERMAL ENERGY SORAGE/HEAT PIPE CONFIG.							

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: POWER MANAGEMENT SYSTEM CONCEPTUAL DESIGN STUDIES

TECHNOLOGY REQUIREMENT

Automatic power system management. Monitor quality of critical electric power system parameters, state and performance of important power distribution, power processing, energy storage, and thermal control equipment. Corrective action in case of out-of-tolerance performance or malfunctions. Protect power system elements against destructive overloads. Provide protection and recycling to arcing transmitter tubes and ensure safe access of maintenance operations. Adjust delivered power by rectenna to varying load demands of power utility.

STATE OF THE ART

~25 kW system

TECHNICAL OBJECTIVES

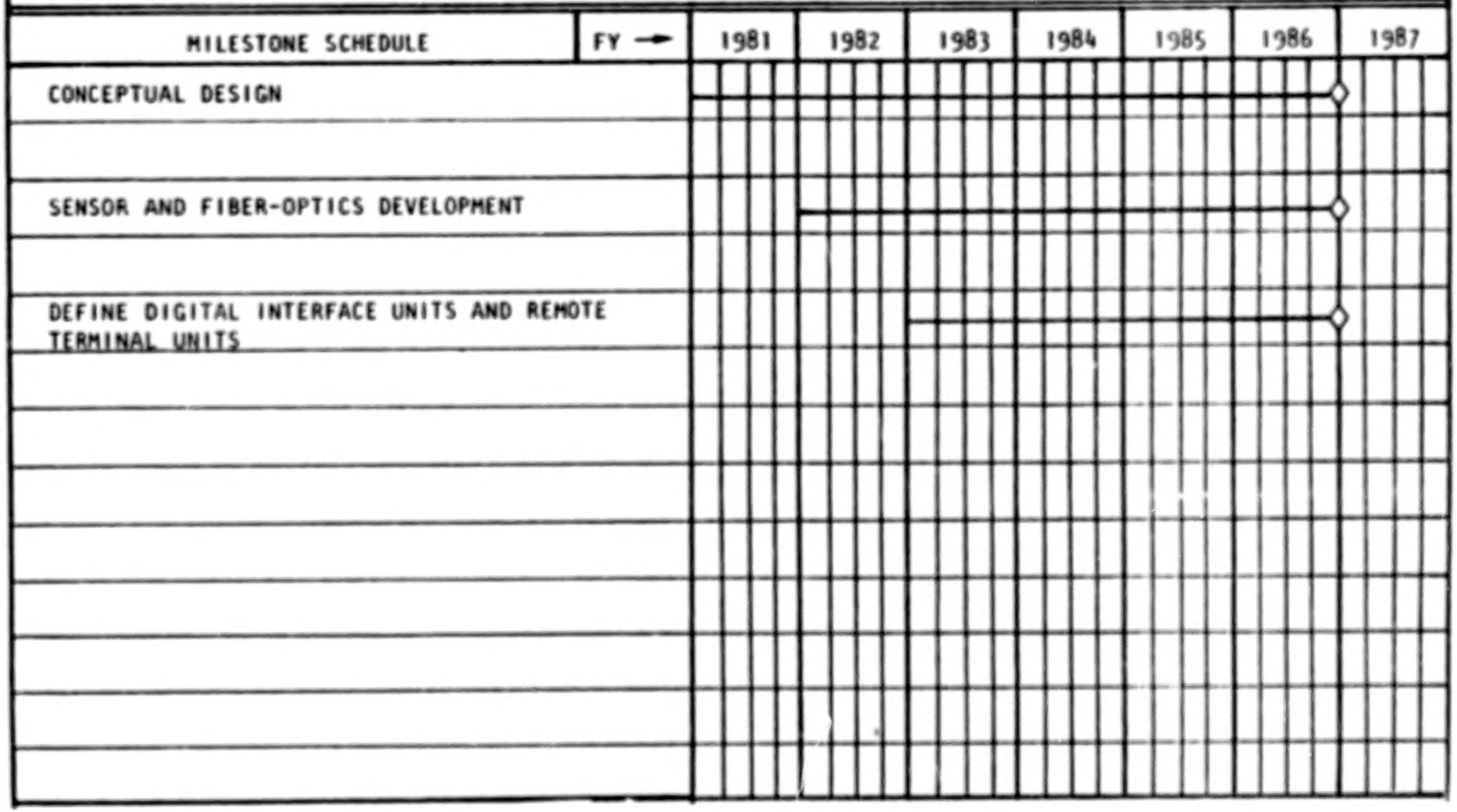
To scope functions and hardware implementation of power management system including development of sensors and fiber-optics needed for analog and digital data transfer and interfacing with high voltage equipment.

TECHNICAL APPROACH

Conduct conceptual design studies to scope the functions and hardware implementation of the power management system, including development of the sensors operating at high voltages and of the fiber optics needed for analog and digital data transfer and interfacing with high voltage equipment. Define the digital interface units and remote terminal units that will become part of the various power distributions, power processing, energy storage, and thermal control equipment. Integrate the power management into SPS design concept.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: POWER MANAGEMENT SYSTEM CONCEPTUAL DESIGN STUDIES



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TECHNOLOGY TITLE: MICROWAVE POWER TRANSMISSION AND RECEPTION TECHNOLOGY

TECHNICAL SUMMARY

The objective of this effort is to conduct critical early analyses and exploratory technology relating to microwave energy transmission and reception key technical issue resolution and fundamental technical feasibility. The tasks in this plan address critical component definition issues relative to microwave power amplification and transmission, ground power rectification, and initial definition of microwave ground test range requirements and characteristics. Computer simulation modeling, experimental lab development and engineering model evaluation will be performed.

TASK SUMMARY

Ground Test Range Definition. No experience exists capable of defining critical technical problems associated with transmission of microwave energy at SPS power levels. Consequently, a need exists to establish performance capabilities and limitations, and associated phenomena for high power transfer from geosynchronous orbit, and to establish preliminary design concept definitions for short range transmission test range, and a ground 1 km linear array antenna.

50 kW Klystron and 5 to 10 kW Magnetron Definition. The objective of this effort is to perform computer aided simulations and establish designs and production processes to optimize and select high power converters. Utilizing the data obtain a definition of capabilities which will enable selection of tube type to accomplish SPS objectives. Harmonics have to be minimized.

RCR Concept Evaluation. Under this effort two developments will be accomplished: 1) a point design RCR/klystron module which meets required pattern, cooling, and cost limitations, and 2) a smaller, lower power output RCR/magnetron. Objectives will include achieving efficiencies on the order of 95%.

MPTS Antenna Pattern Calculation, Alternate Concept Technique Investigation and Power Dipole Optimization. Problems exist with establishing microwave beam patterns through computations; identifying and taking into account all potential deviations from the ideal. The objective of this effort is to develop computer programs for calculation of the MPTS antenna array and line source simulation pattern behavior.

GaAs Diode Concept Evaluation. The objective of this program is to develop diode and rectifier circuit software programs; identify optimum diodes, and establish circuit designs, and evolve efficient fabrication processes.

Power Transistor Preliminary Definition. The objective of this effort is to develop and demonstrate monolithic designs such as GaAs FET and GaAs Bipolar for amplifier chains with ~50 dB gain and 5-50 watt output. Other factors are sensitivity to amplitude changes, aging, and temperature.

Phase Control System. A phase reference power distribution system is required as it maximizes the power transfer to ground from orbit, irnoring the effect of interdicting environment and mechanical distortions. The objective of this effort is to develop and demonstrate a centrally located reference signal transmitter which will provide a reference phase for all conjugation circuits through use of an RF link.

RF Signal Distribution System Development. The solid state subarrays each contain over 16,000 radiating elements and associated power amplifiers. The objective is to establish for the low weight signal distribution systems, the total RF losses, shielding performances, and apply the results to establishing manufacturing, and installation procesures and processes.

High Gain Rectenna Element Development. The objective of this effort is to obtain information for selection and development of the pick-up element for the rectenna portion of the microwave power transmission system. Maximizing sensitivity and efficiency is important, however it cannot be accomplished without paying corresponding penalties in regard to radome protection, maintenance problems, utility interface restrictions, reliability, and life. Also, re-radiation of harmonics has to be minimized.

High Gain Pilot Receiver Antenna Development. During this program pilot antenna designs and installation methods will be investigated and tested to assure pilot signals and power signals are individually capable of discernment, and capable of sustaining the required phase accuracy for beam pointing.

Pilot Transmit System Study and Concept Development. During this effort the relative merits of 3 tone pilot waveform versus large aperture pilot array wavefront techniques will be investigated to optimize the provision of the control signal to the spacecraft conjugation circuits. Effects of ionosphere, weather, aging, etc. will be included. A special effort has to address the jamming resistance of the pilot system.

Study of Alternate Sensing Techniques. On-board monopulse and ground-based amplitude sensors will be studied and developed, to make total beam direction/control fail-safe.

Study of Aperture Distribution Functions, Beam-Steering and Associated Problem Areas. a) Continuous amplitude tapers will be developed (by tapering subarrays also); b) tapers will be optimized for energy trnasfer; c) cost dependency on spacetenna beam steering will be defined.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: GROUND TEST RANGE DEFINITION

TECHNOLOGY REQUIREMENT

A very large percentage of MPTS critical technical issues can be substantially resolved through a comprehensive, progressive microwave transmission ground development program. A more precise definition of required ground test range requirements and facilities is an essential prerequisite to initiation of MPTS subsystem development.

STATE OF THE ART

Little prior experience exists with systems of this magnitude, and careful definition is mandatory.

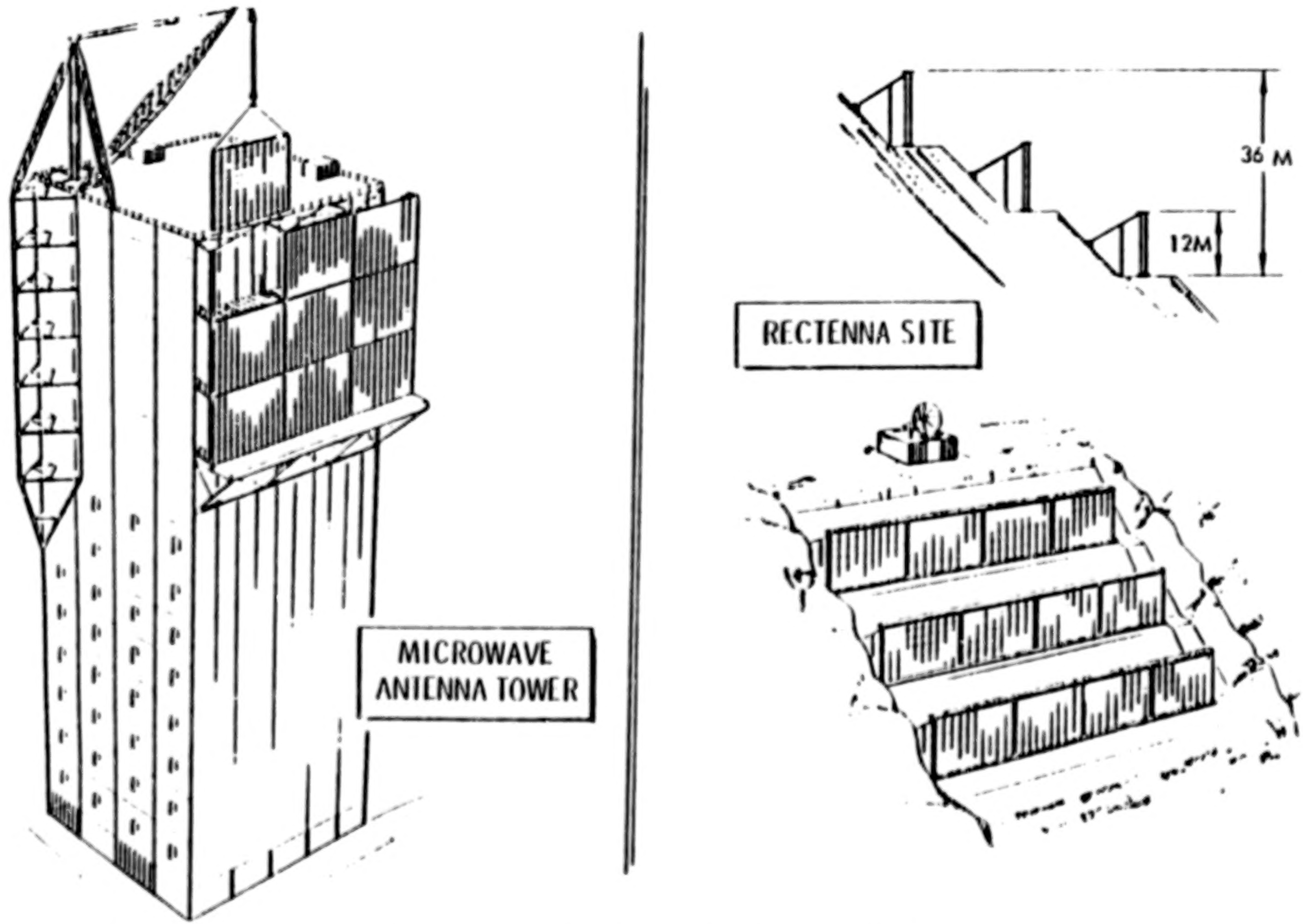
TECHNICAL OBJECTIVES

To determine specific detailed verification test and performance requirements and test system concepts for ground to ground (near-field) and ground to geosynchronous orbit (far-field) verification testing of MPTS subsystem elements, including interface parameters and requirements for a geosat multifunction test system operating in conjunction with a 1 km ground linear array.

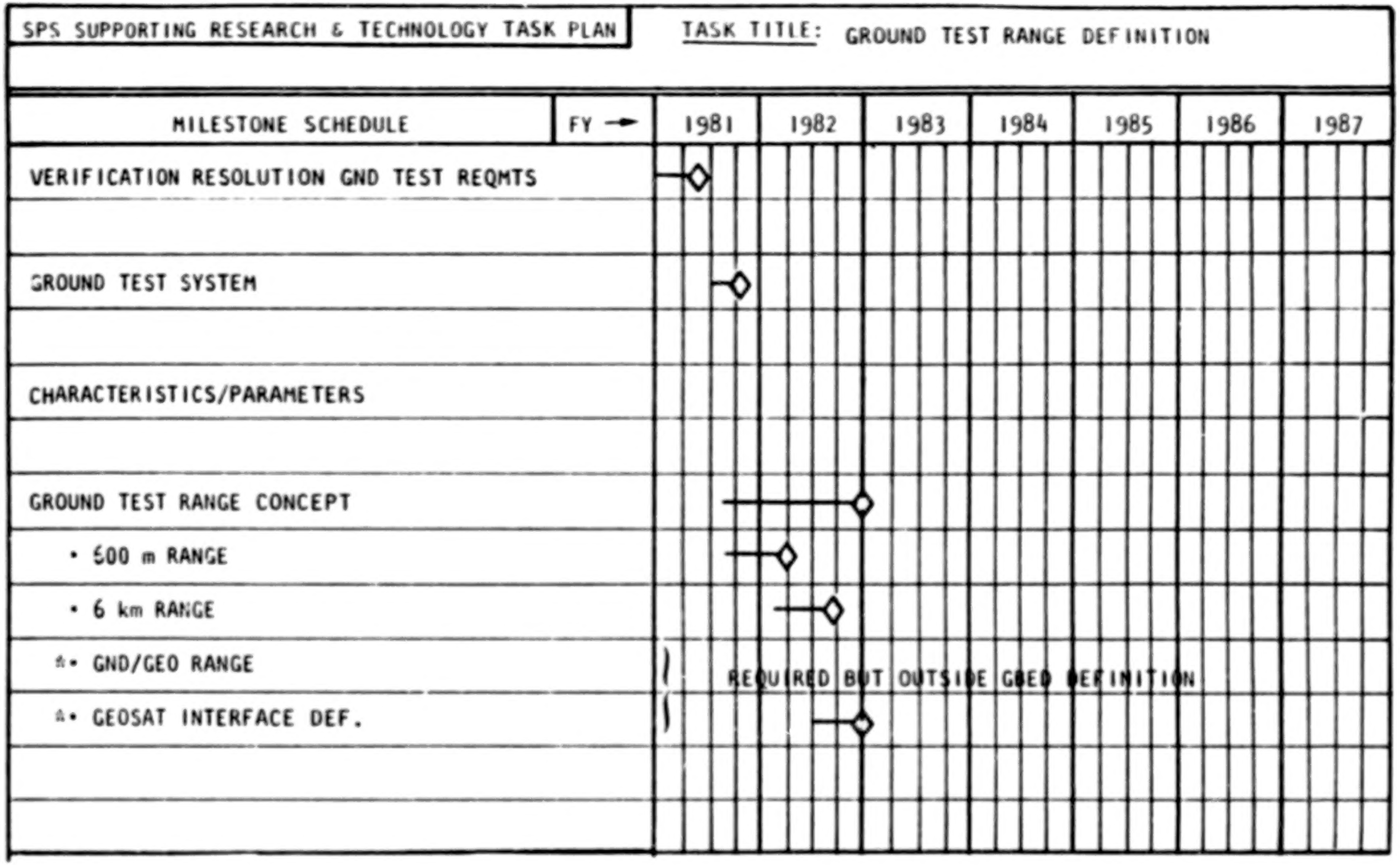
APPROACH

Task sequence will be to establish sequential technical issue resolution requirements, define overall test system characteristics and conduct system concept definition studies for principal ground test elements. The following subtasks will be performed:

- Define MPTS critical technology verification resolution requirements as a parametric basis for proposed test system objectives.
- Describe overall sequential end-to-end MPTS system test characteristics including location, power requirements, instrumentation, etc.
- Develop preliminary design concept definition for 600 meter and 6 km ground to ground test ranges and a ground to geo 1 km linear array antenna installation.



GROUND-TO-GROUND NEAR-FIELD MICROWAVE TEST RANGE



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: GROUND TEST RANGE DEFINITION
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
VERIFICATION RESOLUTION GND TEST REQMTS
GROUND TEST SYSTEM
CHARACTERISTICS/PARAMETERS
GROUND TEST RANGE CONCEPT
• 600 m RANGE
• 6 km RANGE
*• GND/GEO RANGE
*• GEOSAT INTERFACE DEF.
REQUIRED BUT OUTSIDE GBED DEFINITION

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: **50 kW KLYSTRON AND 5 TO 10 kW MAGNETRON DEFINITION**

TECHNOLOGY REQUIREMENT

High-power klystron and magnetron converters must be completely characterized and defined before MPTS design definition can be initiated. Klystron electrical definition requires application of the "floppy disc" digital electron-beam simulation program. Collector electron optics requires analogue simulation. Magnetron electrical definition requires design of single-point, re-entrant feed circuit utilizing either a magic tee (preferred solution) or a circulator to injection lock the magnetron. Noise measurements and complete efficiency calculations/measurements have to be performed. Phase stability loss to be determined for both tubes.

STATE OF THE ART

Current klystrons are inefficient (less than 50%), and considerable improvement is required. Also, if possible, some reduction in AF and FM noise sidebands would be beneficial.

For magnetrons, accurate noise measurements have not been performed, and a low-noise mode (using cold cathodes during operation, i.e., turning off the heater voltage) has only recently been discovered. Another unknown is the injection-lock characteristic using lightweight magic tee circuits. If circulators have be used, a large weight penalty would result.

TECHNICAL OBJECTIVES

Perform computational simulation in a computer-aided-design process to define an optimized SPS klystron, generate initial design and assembly sequences and provide a basis for cost and performance prediction.

Obtain definitive answers for both tubes regarding: (1) efficiency; (2) near-in noise (AM and FM); (3) long-term phase stability; (4) heat transfer characteristics; (5) manufacturability; (6) ease of maintenance; (7) life time; (8) cost for total assembly as used in the SPS; and (9) minimum harmonic output.

APPROACH

- Assemble and proof analogue and digital programs
- Perform klystron/magnetron definition simulation optimization
- Generate design drawings
- Develop assembly flow scenario and instructions
- Build prototype lab models, and test all important parameters listed in the objectives

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN	TASK TITLE: 50 kW KLYSTRON AND 5 TO 10 kW MAGNETRON DEFINITION

MILESTONE SCHEDULE FY →	1981	1982	1983	1984	1985	1986	1987
ANALOG-DITITAL PROGRAM-ASSEMBLY & ANALYSIS							
GENERATE KLYSTRON & MAGNETRON DESIGN & OPTIMIZE							
GENERATE DESIGN DRAWINGS							
GENERATE ASSEMBLY FLOW & PROCEDURES							
FAB & TEST PROTOTYPE LAB MODEL							

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: RCR CONCEPT EVALUATION

TECHNOLOGY REQUIREMENT

An integrated microwave—radiator/power converter module must be characterized and developed in detail as a necessary prerequisite to point-design MPTS performance, mass and cost determinations.

STATE OF THE ART

Preliminary tests have shown about ~75% efficiency. This needs to be improved (as for the ordinary waveguide array) to 95%.

TECHNICAL OBJECTIVES

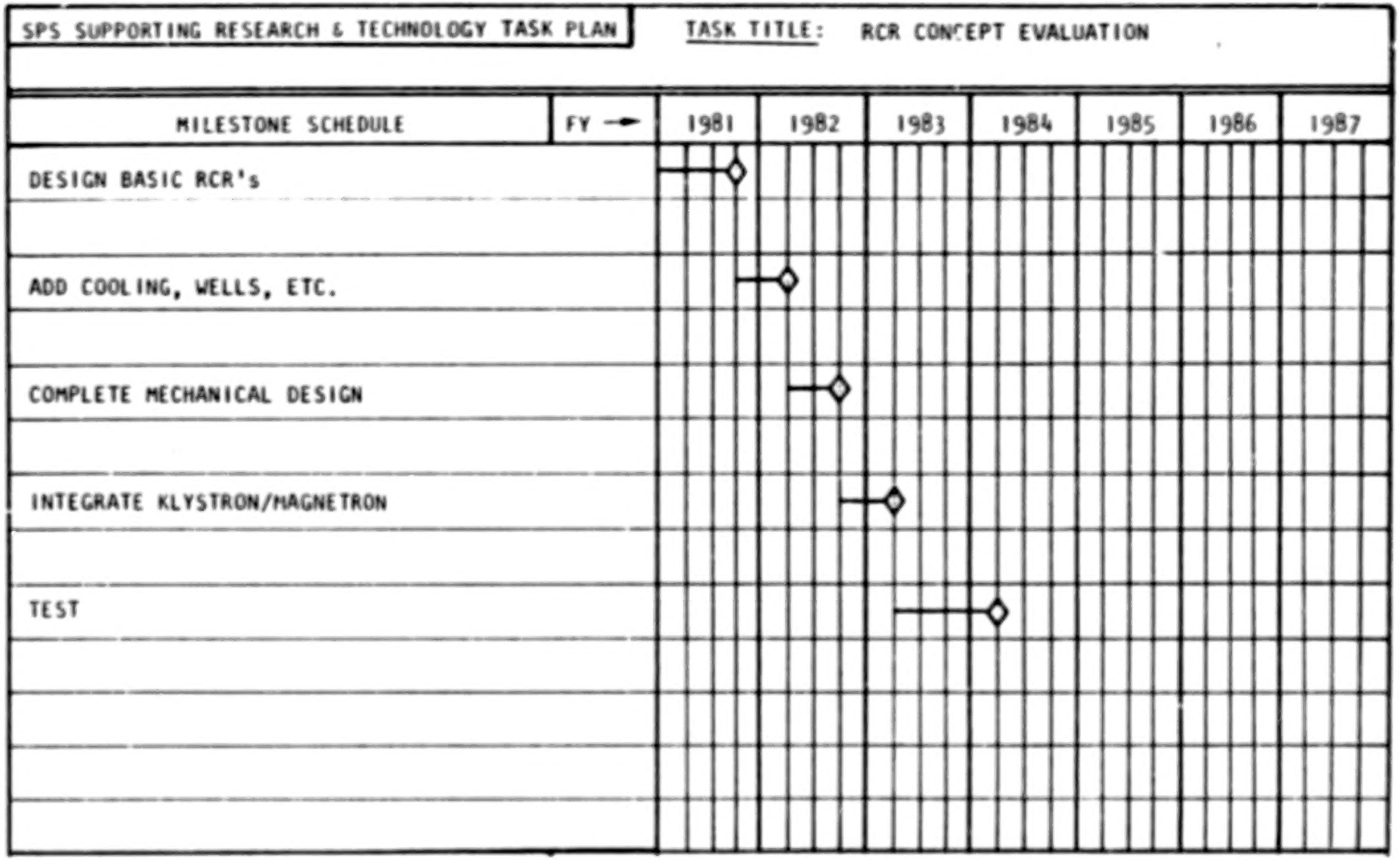
Perform development of a point-design RCR/Klystron module with required pattern, adequate cooling and an economical manufacturing process. Ohmic loss will be considered a major parameter.

Alternately, RCR/Magnetron modules will be investigated, with lower power tube outputs and hence smaller RCR sizes.

APPROACH

Resonant cavity resonator configurations of various characteristics will be designed and evaluated. Variants will include feeder placement, introduction of the klystron/magnetron well, addition of heat-pipe grid, and use of choke joints for assembly. Experimental model will be tested in a space simulator for cooling performance, multipaction, temperature distribution and other performance characteristics.

Proper design of the critical contact surfaces will be the key issue in increasing the efficiency.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: RCR CONCEPT EVALUATION
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
DESIGN BASIC RCR's
ADD COOLING, WELLS, ETC.
COMPLETE MECHANICAL DESIGN
INTEGRATE KLYSTRON/MAGNETRON
TEST

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MPTS ANTENNA PATTERN CALCULATION, ALTERNATE CONCEPT TECHNIQUE INVESTIGATION AND POWER DIPOLE OPTIMIZATION

TECHNOLOGY REQUIREMENT

Microwave beam computed patterns taking into account all deviations from ideal behavior are required for projected point-design MPTS antenna concepts prior to developmental hardware testing. Later ground to GEO line array pattern measurements must correlate well with antenna pattern modeling to verify antenna design adequacy. Antenna behavior is intimately tied to beam control technique. Alternate techniques (baseline: retrodirective) need to be evaluated. Also, the electrical characteristics of the power dipole have to be optimized.

STATE OF THE ART

Far-out sidelobe level in very large arrays have to be determined on a probabilistic basis. The University of Illinois under Professors Lo, Lee and Mittra is concurrently seeking a grant from the NSF to investigate phase error effects on sidelobes and total efficiency in very large array. Their techniques (assuming they will be funded) can be utilized in the SPS technology support program.

TECHNICAL OBJECTIVES

Assemble a specialized computer program for calculation of MPTS antenna array and line source simulation pattern behavior. Use probabilistic techniques to determine the effects of tolerances (mostly phase errors) on far-out sidelobes, which in turn can reduce beam efficiency substantially.

APPROACH

- Construct an optimized computer program using as subprograms, existing programs for computing line and planar array patterns from the array excitation.
- The main program will identify excitation functions by calling subprograms which generate perturbations of the ideal excitations generated in the MAINGO.
- Evaluate and utilize the following subprograms: (as a starting point.)

• MAINGO	• WEIGHT	• RECTNA
• LOCATE	• XFORM1	• PRTPLT
• RETRO	• XFORM2	• CRTPLT
• STEER	• VALUES	• TBLPLT

- Utilize University of Illinois techniques to the extent available.

Evaluate effect of systems configuration on sidelobe performance; efficiency; steering accuracy, etc. Include alternate steering mechanisms. Emphasize probabilistic approach.

Analyze thin dipole performance. Optimize for array environment; integrate with amplifier.

Coordinate the efforts in this task with study of "Alternate Sensing Techniques" and with study of "Aperture Distribution Functions and Associated Problems." Establish cost versus steering angle for single spacetenna, multiple rectenna systems.

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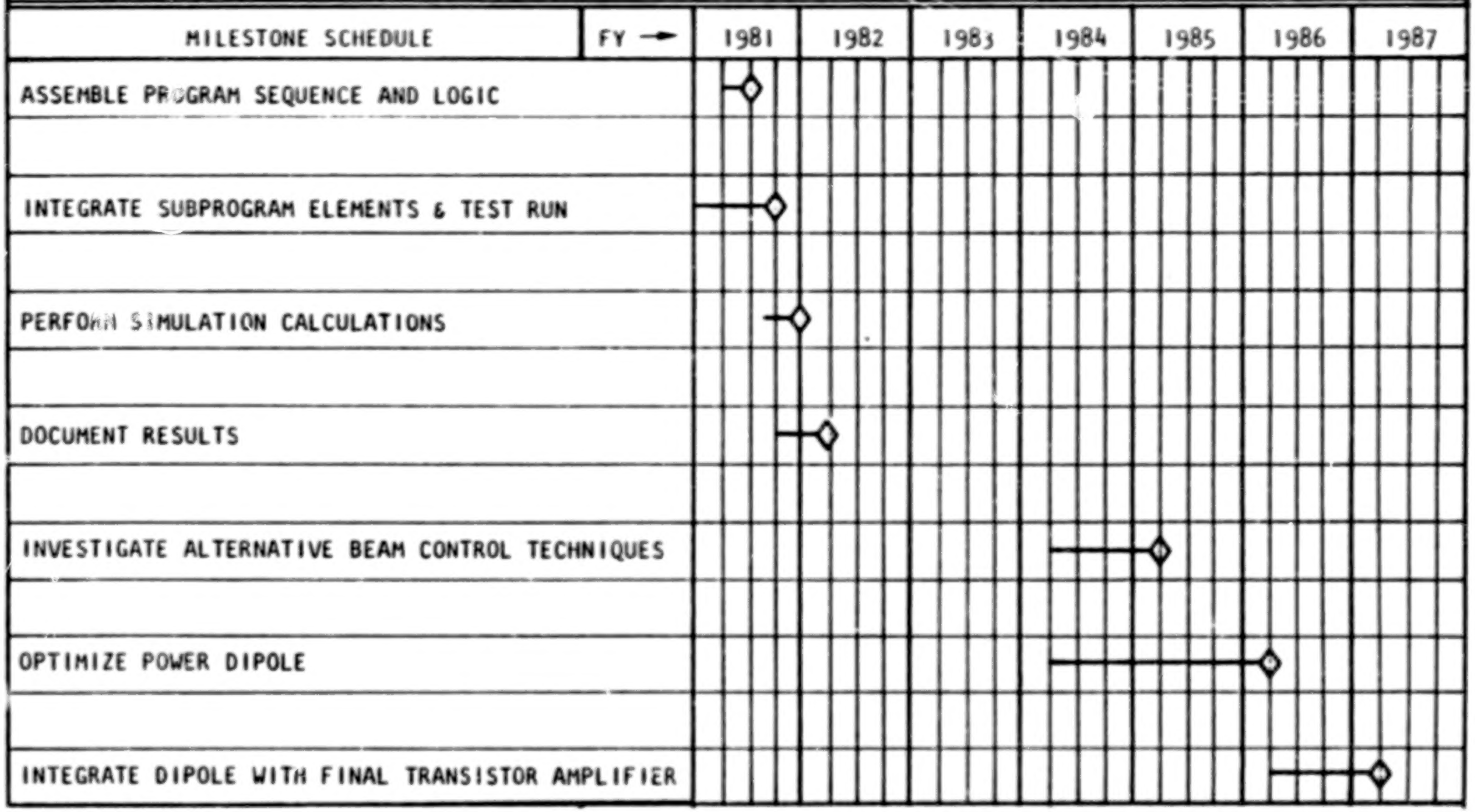
SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MPTS ANTENNA PATTERN CALCULATION, ALTERNATE CONCEPT TECHNIQUE INVESTIGATION AND POWER DIPOLE OPTIMIZATION



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: GaAs DIODE CONCEPT EVALUATION

TECHNOLOGY REQUIREMENT

Diode and corollary rectifier circuits must be characterized and developed as a prerequisite to SPS rectenna configuration definition and cost and performance optimization.

STATE OF THE ART

Only half-wave rectifiers have been optimized in connection with single low-gain diodes. Different (high-gain) elements will require different diode characteristics. Also, full-wave rectification needs to be evaluated.

TECHNICAL OBJECTIVES

Develop diode and rectifier circuit software programs, evolve optimum diode and circuit design and evolve efficient fabrication processes. Inasmuch as problems in defining GaAs parameters are the same as for the GaAs transistor program task, perform this task in parallel.

APPROACH

The development of the diode CAD program can be a simplification of the Waterloo transistor program, BIPOLE. As in the transistor case either WATAND or REPAC can be used for the CAD rectifier circuit program. Test diodes are then made and compared with the computer program results. GaAs parameters and structure data is modified according to lab results then new designs are run. This will continue until an optimum design is obtained.

Rectenna performance will then be calculated in light of the optimum design parameters.

Finally large-scale manufacture methods will be projected from the laboratory fab processes and volume production costs estimated.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN	TASK TITLE: GaAs DIODE CONCEPT EVALUATION

MILESTONE SCHEDULE	FY → 1981	1982	1983	1984	1985	1986	1987
WRITE PROGRAM							
COLLECT GaAs DATA							
CAD DESIGN							
RECYCLE DESIGNS TO OBTAIN OPTIMUM							
MANUFACTURE RECTENNA							

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: POWER TRANSISTOR PRELIMINARY DEFINITION

TECHNOLOGY REQUIREMENT

A preliminary concept definition and performance evaluation of three transistor power converters must be performed as a basis for the power module point design decision by 1982 prior to component development and verification. Additional heavy development is required in the areas of GaAs bipolar transistors (so far mostly FET's have been considered), and complete monolithic construction of 3 to 5 stage amplifiers. Integration with the dipole radiator must be proven.

STATE OF THE ART

70% efficiency has been achieved with a single GaAs FET. However, temperature capability needs to be improved somewhat. Also, total amplifier chain characteristics for 5 watt (and especially 50 watt) output at S-band with concomitant gains of ~50 dB are not known. Finally, cost and weight constraints require ultimately that monolithic techniques be employed. Previous monolithic designs are sketchy and do not address specific SPS needs.

TECHNICAL OBJECTIVES

Evaluate the performance and S-O-A manufacturing potential for advanced power transistor development for application to MPTS power amplification. Prove monolithic designs (both GaAs FET and GaAs Bipolar) for complete amplifier chains with ~50 dB gain and ~5 (50) watt output.

APPROACH

Task will consist of an iterative process of data acquisition on GaAs parameters, calculation of optimized transistor performance and evaluation of production potential.

The task sequence includes the following:

a) Collection of preliminary GaAs parametric data

b) CAD design of transistor using variation of Waterloo program—BIPOLE

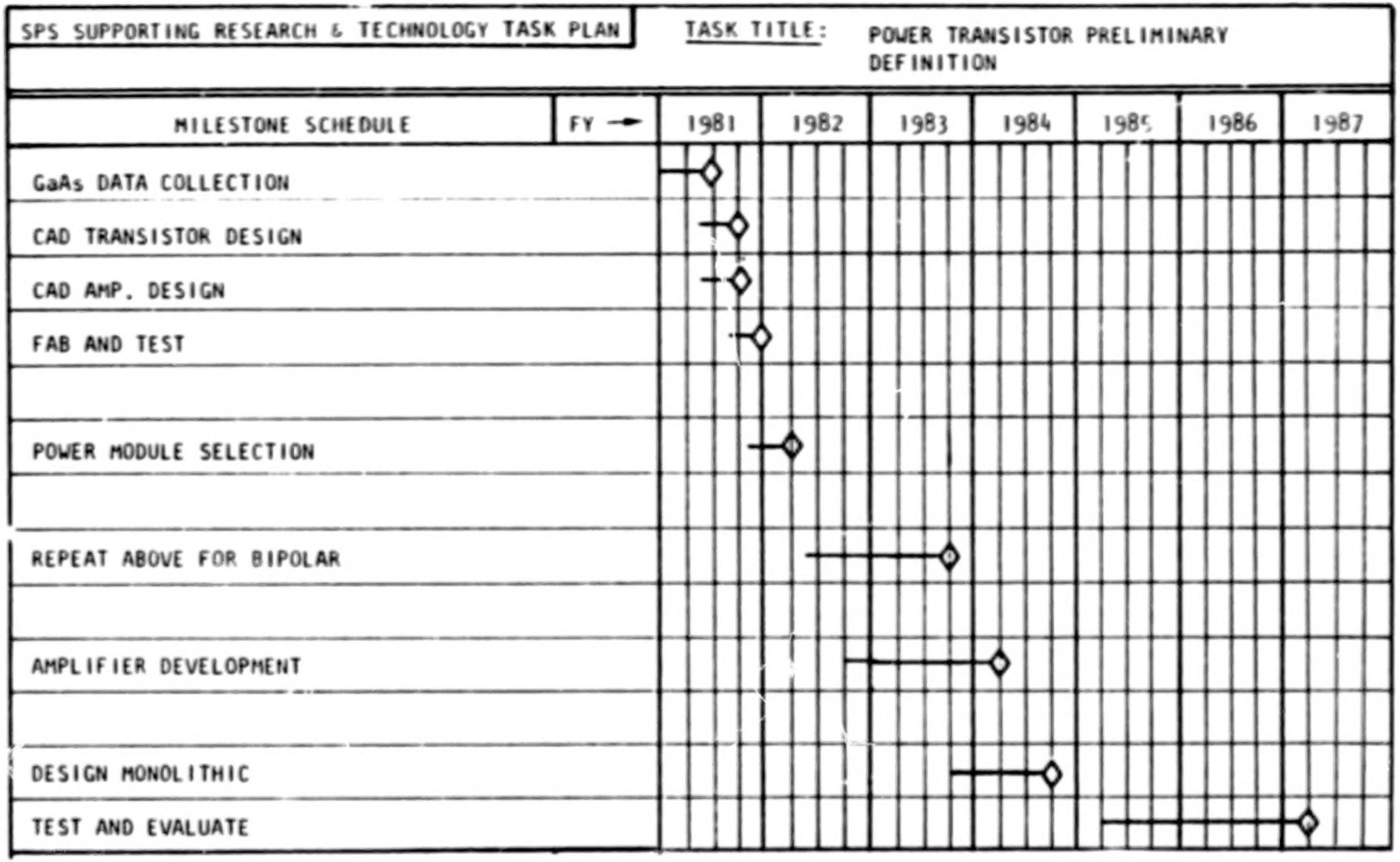
c) CAD design of amplifier circuits using either Waterloo—WATAND or RI—REPAC

d) Fabrication and test evaluation of transistor and amplifier performance

e) Refinement of GaAs data and efficiency projection

Repetition of a) through e) for Bipolar.

Building of lab models in discrete and monolithic technology, with ultimate goal of integration with power dipole in simulated array environment.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE:
POWER TRANSISTOR PRELIMINARY DEFINITION
MILESTONE SCHEDULE
FY
1981
1982
1983
1984
1985
1986
1987
GaAs DATA COLLECTION
CAD TRANSISTOR DESIGN
CAD AMP. DESIGN
FAB AND TEST
POWER MODULE SELECTION
REPEAT ABOVE FOR BIPOLAR
AMPLIFIER DEVELOPMENT
DESIGN MONOLITHIC
TEST AND EVALUATE

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: PHASE CONTROL SYSTEM

TECHNOLOGY REQUIREMENT

It is very important to develop a reference phase distribution system, and a phase conjugation circuit, which can point the power beam of the SPS with maximum accuracy at the center of the rectenna site. The phase reference should be distributed in such a way that mechanical distortions have no effect on the beam steering accuracy and/or the beam efficiency; and without connections between subarrays.

STATE OF THE ART

Preliminary tests have been performed on a varity of conjugation networks, but never to the degree of phase accuracy required for the low sidelobe levels necessary in the SPS for maximum efficiency and minimum beam steering error. Furthermore, the distribution system for the reference phase considered by Boeing, and investigated by LINCOM, requires cross-connections of an elaborate wire network, and extremely complex phase regeneration circuits.

TECHNICAL OBJECTIVES

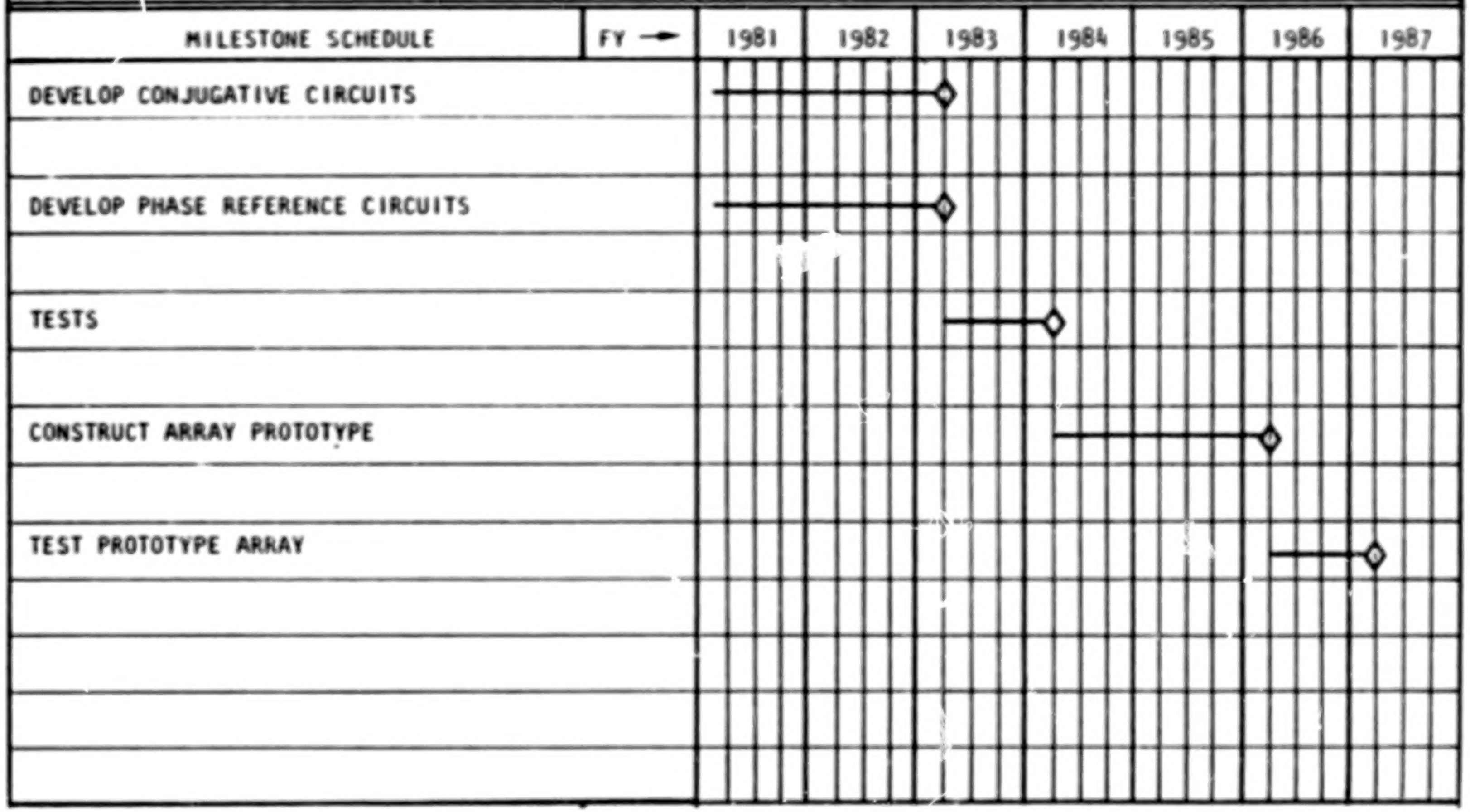
A better approach will be developed in this task, i.e., a centrally located (either in-plane or out-of-plane) reference signal transmitter, which will not only provide a standard reference phase for all conjugation circuits, but also achieve this via a radio link, i.e., without requirement for interconnecting the subarrays with multiple transmission lines.

TECHNICAL APPROACH

A radio distribution system consists of two essential parts; the central transmitter, and the reference phase compensation circuit which eliminates the effects of distortions in the phased array aperture. Once a uniform phase reference is established, the ground based pilot signal can be conjugated, and the power beam is steered in the proper direction. The conjugation circuit is thus the third essential network ingredient for the phase control system. Both for the reference phase distribution and for the pilot tone reception 3 frequencies will be transmitted to allow on-board compensation at aperture distortion and of ionospheric time delay variations across the control beam. These circuits will be developed and tested.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: PHASE CONTROL SYSTEM



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: RF SIGNAL DISTRIBUTION SYSTEM DEVELOPMENT

TECHNOLOGY REQUIREMENT

Each solid-state subarray (both end-mounted and sandwich configurations) contains over 4,000 radiating elements, with at least that many associated power amplifiers. A minimum weight signal distribution system (from the subarray conjugation circuit output to the input of each amplifier) has been conceptually developed, which will use coaxial or hybrid coax/stripline feed lines. The exact layout, type of coax and/or other material and their total loss and shielding performances need to be studied, and manufacturing techniques investigated.

STATE OF THE ART

Using several layers of Kapton in a pure stripline configuration has been found to be either extremely lossy, extremely heavy, or both. Using a thinned all-coaxial system results in minimum weight, but substantial problems may arise due to launch vibrations. No useful signal distribution system is known, however, which has a lighter total weight, particularly if alumina dielectrics are used instead of Kapton. It is important, therefore, to increase the knowledge of signal distribution systems, because they are a major parameter in the solid-state designs.

TECHNICAL OBJECTIVES

Pure coaxial networks will be studied, with emphasis on optimum geometry (layout within a single layer is preferred), on interconnections (e.g., ultrasonic weld, solder, crimp, etc.) and on packaging to withstand the launch environment. A secondary issue is interconnection in space of manufacturing modules to create a complete subarray, with current dimensions of 5 meters by 5 meters.

TECHNICAL APPROACH

The basic feed circuit geometry is fairly well determined by the fact that the total element number is binary. A layout will be studied which distributes the signal from the central point in onle layer to each amplifier input, including Wilkinson hybrids at the last power split. Methods will be developed to produce the transmission line pieces in a maximally random fashion, so that phase errors are randomized. An alternate approach will be studied using Kapton stripline circuits. Proper interconnect techniques are crucial and attention will have to be given to possible feedback loops. For both hases, loss and weight will have to be minimized, and protection techniques (e.g., form) established. Several lab models will be designed and tested electrically; mechanically and environmentally.

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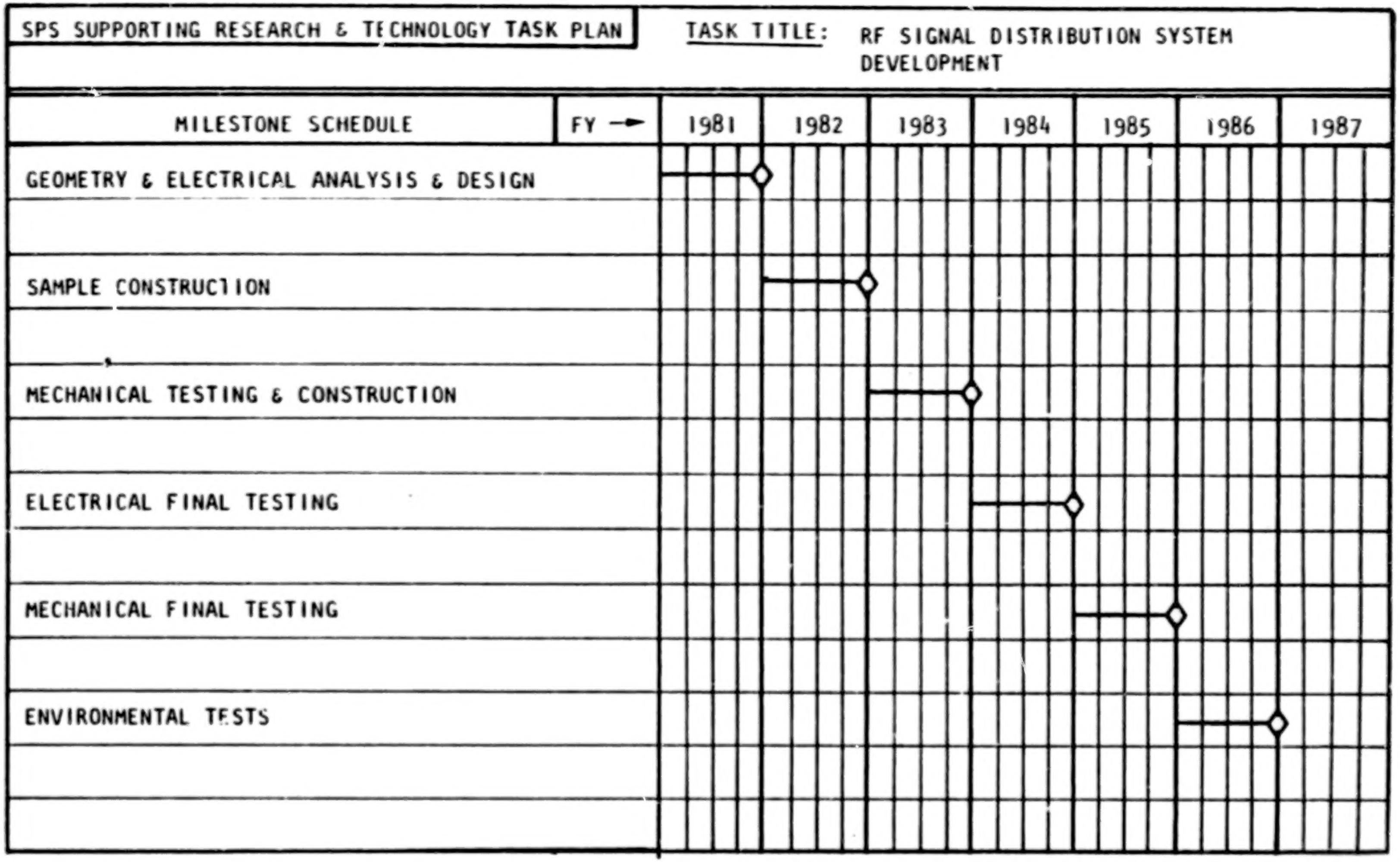
	4.4.4 SPS Concept Comparisons	4-28	1/F14
	4.4.5 SPS Comparative Investment Assessment	4-32	1/G5
5.0	SUPPORTING RESEARCH AND TECHNOLOGY REPORTS	5-1	1/G6


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: RF SIGNAL DISTRIBUTION SYSTEM DEVELOPMENT
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
GEOMETRY & ELECTRICAL ANALYSIS & DESIGN
SAMPLE CONSTRUCTION
MECHANICAL TESTING & CONSTRUCTION
ELECTRICAL FINAL TESTING
MECHANICAL FINAL TESTING
ENVIRONMENTAL TESTS

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: **HIGH-GAIN RECTENNA ELEMENT DEVELOPMENT**

TECHNOLOGY REQUIREMENT

To provide the highest efficiency pick-up element for the rectenna portion of the microwave power transmission system. At the time, total cost (life-cycle) has to be minimized with regard to random protection, maintenance problems with the utility interface and overall reliability, e.g., W.R.T. lightning protection, also the harmonics generated by the rectenna; and RFI generated thereby, have to be analyzed and minimized. High-gain elements may offer substantial advantages over low-gain elements, and require detailed study.

STATE OF THE ART

So far only simple dipoles have been used in connection with half-wave rectifiers. Full-wave rectification costs more, and the large number of low-gain dipoles has prevented much investigation of alternate schemes. Certain types of helices and parasitic elements such as cigar antennas and yagis, have highly efficient modes (approaching 100%), and yet offer gains of 10 to 16 decibels. Reflector, particularly low F/D ratio paracylinders, can have gains of ~20 decibels. This allows a reduction of element number to one tenth, or to ~ one hundredth.

TECHNICAL OBJECTIVES

Provide definitive design information regarding size, capture area, capture efficiency impedance match, harmonic radiation characteristics, lightning protection and ease of maintenance. Test representative designs, and provide inputs to a design and test program for a large-scale prototype (or two, one using e.g., yagis and one using reflectors) to be evaluated further in a ground based test system for end-to-end transmission efficiency.

TECHNICAL APPROACH

The following high-gain antenna demands will be studied:

1. Helices, particularly those operating in a high-efficiency mode at the lower end of the design bandwidth.

2. Yagis, i.e., linear parasitic arrays with linear polarization.

3. Cigar antennas (also called disc-on-rod), with linear polarization.

4. Parabolic cylinder antennas with very short focal length for high efficiency, and their associated radisines.

5. Line source (i.e., traveling-wave) feeds for paracylinder antennas with a minimum number of feed points for additional reduction in component number.

6. Multiple element feeds for paracylinders, using high-gain elements (see 1 through 3 above).

7. Low-gain feed elements for paracylinder antennas. After technical design optimization other factors will be used for final evaluation, such as, ease of maintenance and hook-up to U.I., reliability, and RFI generation (suppression).

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: HIGH GAIN RECTENNA ELEMENT DEVELOPMENT

MILESTONE SCHEDULE	FY → 1981	1982	1983	1984	1985	1986	1987
STUDY HELIXES, YAGIS, CIGARS							
STUDY REFLECTOR CONFIGURATIONS & RADOMES							
STUDY LINE SOURCE FEEDS							
STUDY MULTI-ELEMENT FEEDS							
STUDY ALTERNATE LOW-GAIN ELEMENTS & REFLECTOR FEEDS							
EVALUATE RELATIVE MERITS W/REGARD TO UTILITY INTERFACE, RFI, MAINTAINABILITY, & RELIABILITY							

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: HIGH-GAIN PILOT RECEIVER ANTENNA DEVELOPMENT

TECHNOLOGY REQUIREMENT

Depending on the type of SPS array (baseline waveguide slot modules, or solid-state arrays with power dipoles) pilot antennas have to be located either at the edges of the subarrays or in the center. In either case high-gain end fire arrays (Yagis, helices) can be used, or arrays of low-gain elements. The crucial parameter for all of these antennas is rejection of the power signal, thru cross-polarization and location, as well as feed design.

STATE OF THE ART

Not much development work has been done. Optimization of gain versus power signal rejection has not been performed, only general, possible locations being identified. The current state of the art is totally inadequate, and no assurance exists that the pilot receiver front end will not be saturated by the power signal. Notch filtering is only of limited usefulness, because several pilot frequencies may have to be used.

TECHNICAL OBJECTIVES

The totality of available pilot antenna designs compatible with the subarray construction and layout, need to be investigated to achieve (given a fixed pilot ground station ERK and a fixed amount of filtering) a pilot-to-power signal ratio capable of sustaining the required phase accuracy for beam pointing.

TECHNICAL APPROACH

The following antenna types will be investigated and developed:

1. High-gain helices, constructed of lightweight hollow tubes with deposited filament.

2. Yagis (linear arrays of parasitic dipoles).

3. Cigar antennas.

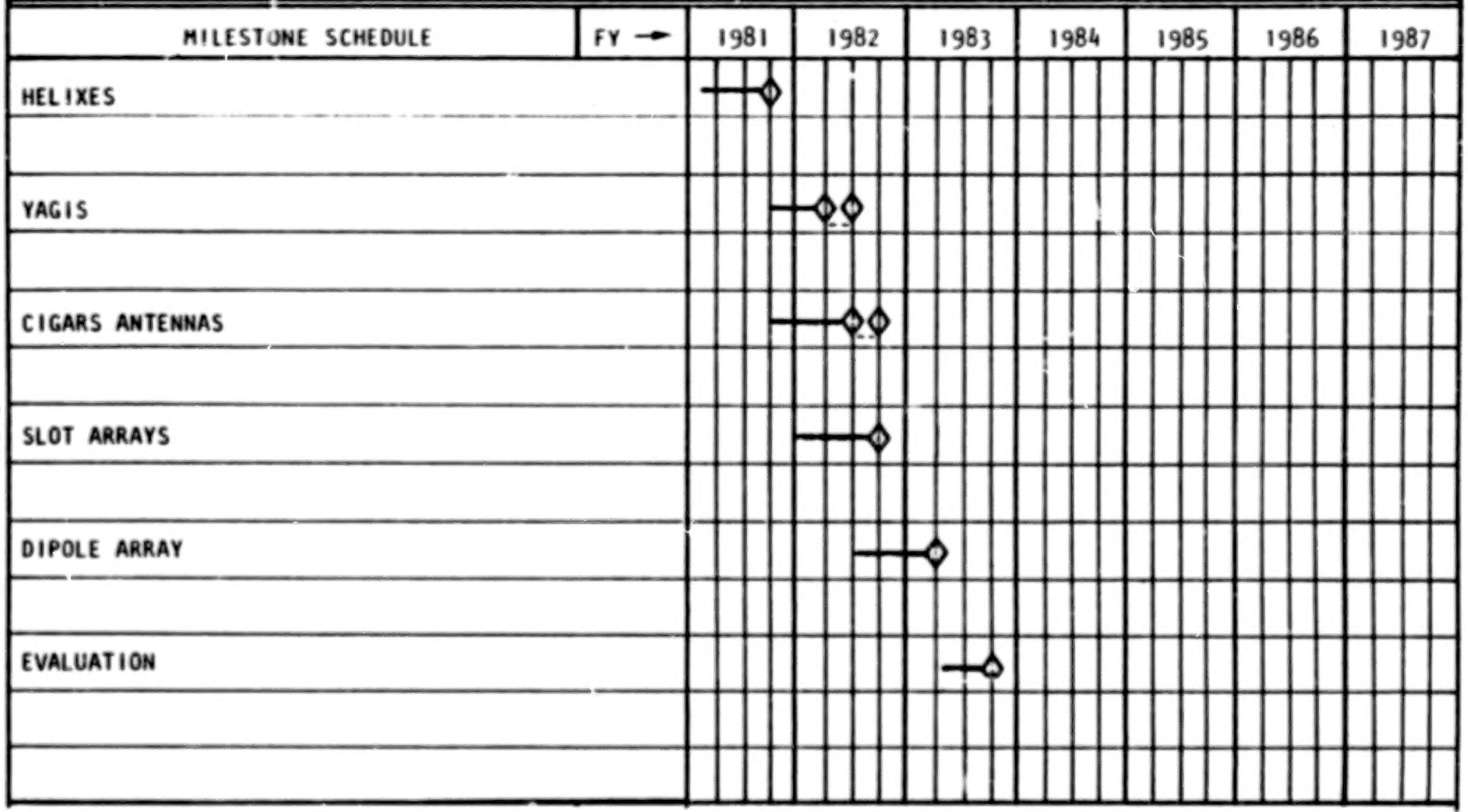
4. Arrays of slots in the subarray ground plane.

5. Arrays of orthogonal, shortened dipoles with either direct or coupled feeds.

The antennas will primarily be designed for minimum coupling to the adjacent power dipole of the SPS array for simplicity of construction and installation and for maximum reliability at the signal output. Efficiency, etc., are of secondary importance.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: HIGH GAIN PILOT RECEIVER ANTENNA DEVELOPMENT



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: PILOT TRANSMIT SYSTEM STUDY AND CONCEPT DEVELOPMENT

TECHNOLOGY REQUIREMENT

The ground based pilot transmitter has to provide the control signal for the spacecraft conjugation circuits with maximum reliability, and with a waveform and/or wavefront design which is unaffected by ionospheric vagaries weather conditions, aging, etc. Both the general conjugation principle and specific circuits need to be studied (Pilot transmitter in center of rectenna or offset), and the waveform/wavefront design for ionospheric effects which could produce steering errors or efficiency loss.

STATE-OF-THE-ART

Only a small (~15 foot) reflector with a few kilowatts of power has been considered so far as a typical pilot transmit system located in the center of the rectenna. Ionospheric effects elimination is generally achieved by a 3-tone pilot signal, which allows measurement and compensation of ionospheric delays. Only recently a large circular pilot array was proposed.

TECHNICAL OBJECTIVES

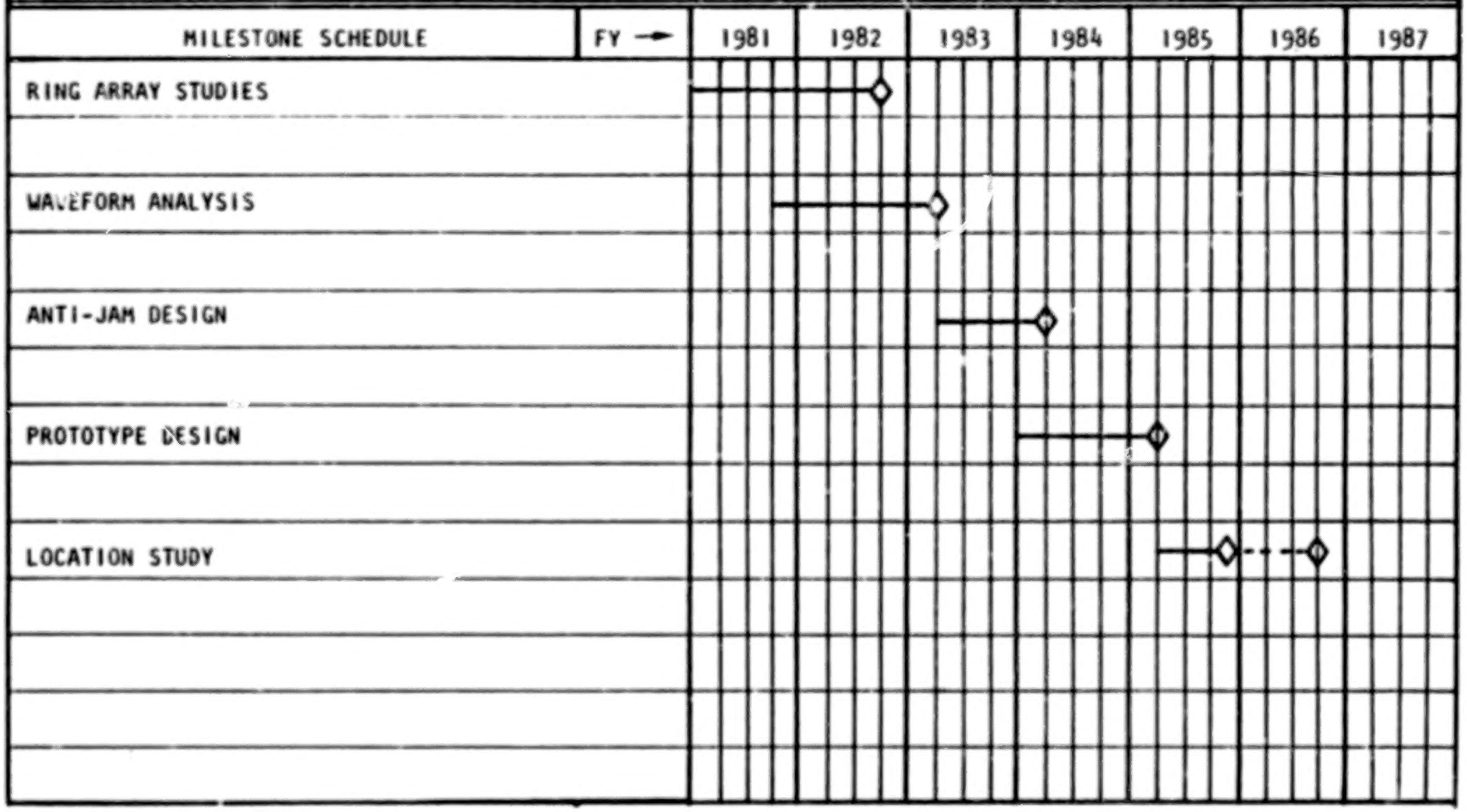
Investigate relative merits of waveform (3 tone pilot) versus wavefront (large aperture pilot array with high reliability, high ERB, and minimal susceptability to stationary and fluctuating ionspheric disturbances). Design pilot system combining the best features of both approaches, so as to have an absolutely fool-proof design beyond reproach.

The following tasks shall be performed:

1. Investigate various single-ring and multi-ring circular arrays for producing a wide power tube into the ionosphere, with little or no susceptability to disturbances.
2. Design waveforms capable of providing additional protection against atmospheric and ionospheric disturbances.
3. Design anti-jam features into waveform.
4. Design prototype pilot array using ~10,000 elements and ~120-kW transmitted power.
5. Study center locations and offset locations W.R.T. minimizing conjugation circuit complexity.
6. Coordinate with alternate steering techniques to integrate pilot system into those techniques.
7. Coordinate with alternate sensing techniques.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: PILOT TRANSMIT SYSTEM STUDY AND CONCEPT DEVELOPMENT



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ALTERNATE DIRECTION SENSING TECHNIQUES

TECHNOLOGY REQUIREMENT

The current reference systems (both tube-type and solid-state) and the sandwich system all use retrodirectivity for both beam direction sensing and beam steering. A viable alternative is to separate beam steering, phase control, and direction sensing of the ground-based pilot.

STATE-OF-THE-ART

Monopulse sensing systems can betermine the direction of an arriving system with a "beam splitting factor" (improvement over the 3 dB beamwidth criterion) of 50 for high signal-to-noise ratios. This means that a relatively small on-board aperture can be used to determine the beam direction of the power beam.

TECHNICAL OBJECTIVES

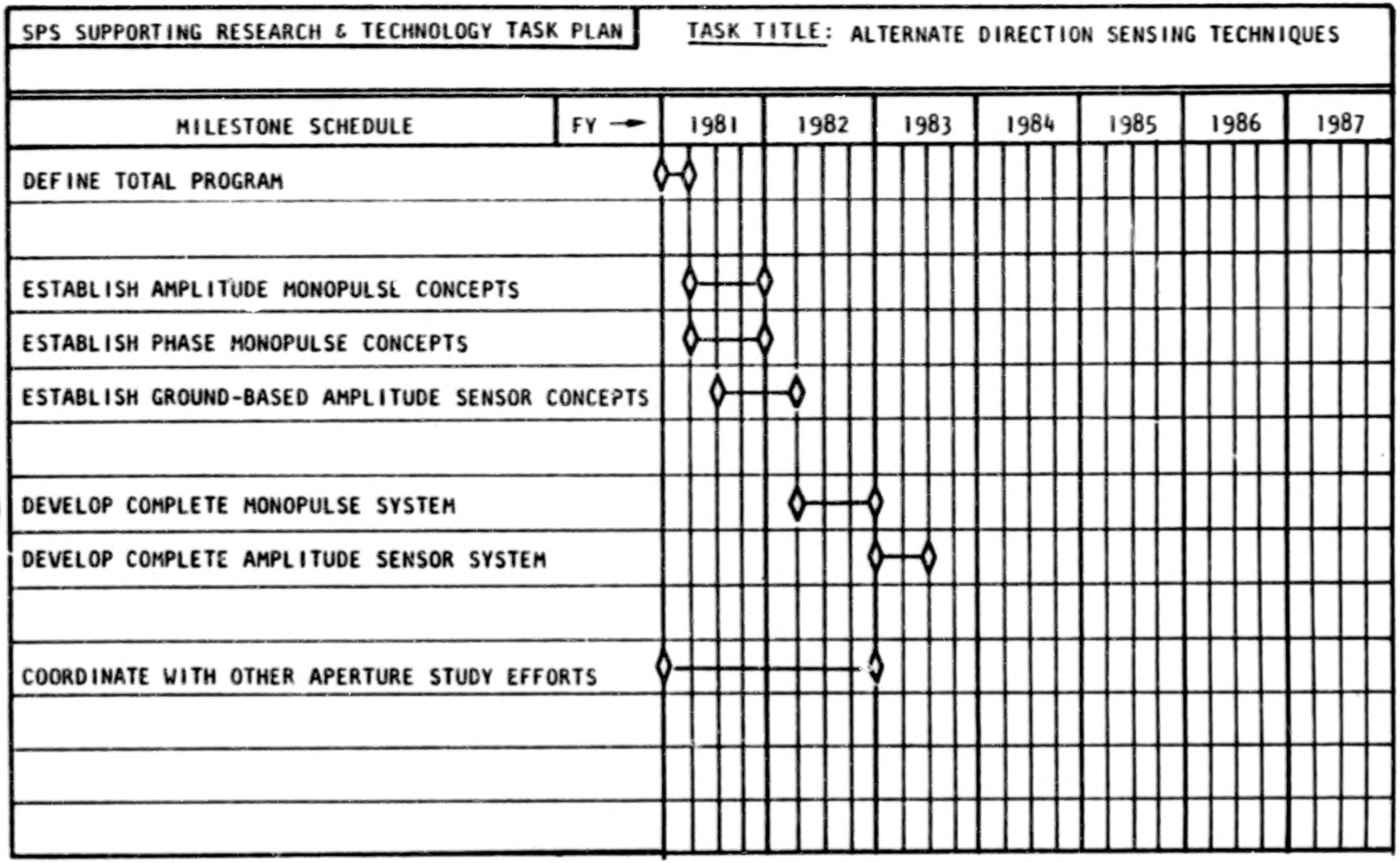
To investigate amplitude and phase monopulse techniques and ground-based amplitude sensors, to determine the required direction of transmission for the power beam.

APPROACH

a) Determine linear monopulse array size required for accurate direction sensing in two orthogonal planes. Establish complete system design.

b) Develop system of ground based amplitude sensors with inputs to on-board steering control system.

c) Coordinate with tasks on "Aperture Distributions" and "Pilot System Concept Study", as well as 'Pattern Calculations...."


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: ALTERNATE DIRECTION SENSING TECHNIQUES
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
DEFINE TOTAL PROGRAM
ESTABLISH AMPLITUDE MONOPULSE CONCEPTS
ESTABLISH PHASE MONOPULSE CONCEPTS
ESTABLISH GROUND-BASED AMPLITUDE SENSOR CONCEPTS
DEVELOP COMPLETE MONOPULSE SYSTEM
DEVELOP COMPLETE AMPLITUDE SENSOR SYSTEM
COORDINATE WITH OTHER APERTURE STUDY EFFORTS

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: APERTURE DISTRIBUTION FUNCTIONS AND ASSOCIATED PROBLEMS

TECHNOLOGY REQUIREMENT

To achieve a high beam efficiency, an array amplitude taper may be desirable. This can be approximated in a stair-step function, but advanced distributions require smooth, continuous tapers across the aperture, i.e., an amplitude variation across the subarray also. This will reduce sidelobes as compared to the stair-step approximation. The problem is particularly pertinent to the solid-state sandwich approach, where only a uniform amplitude distribution has been postulated so far.

STATE-OF-THE-ART

Current phased array art allows the design of distributions which places zeros at the proper places for shaping the sidelobe envelope. There are rotationally symmetric distributions with low Q, adjustable sidelobe level and high efficiency.

TECHNICAL OBJECTIVES

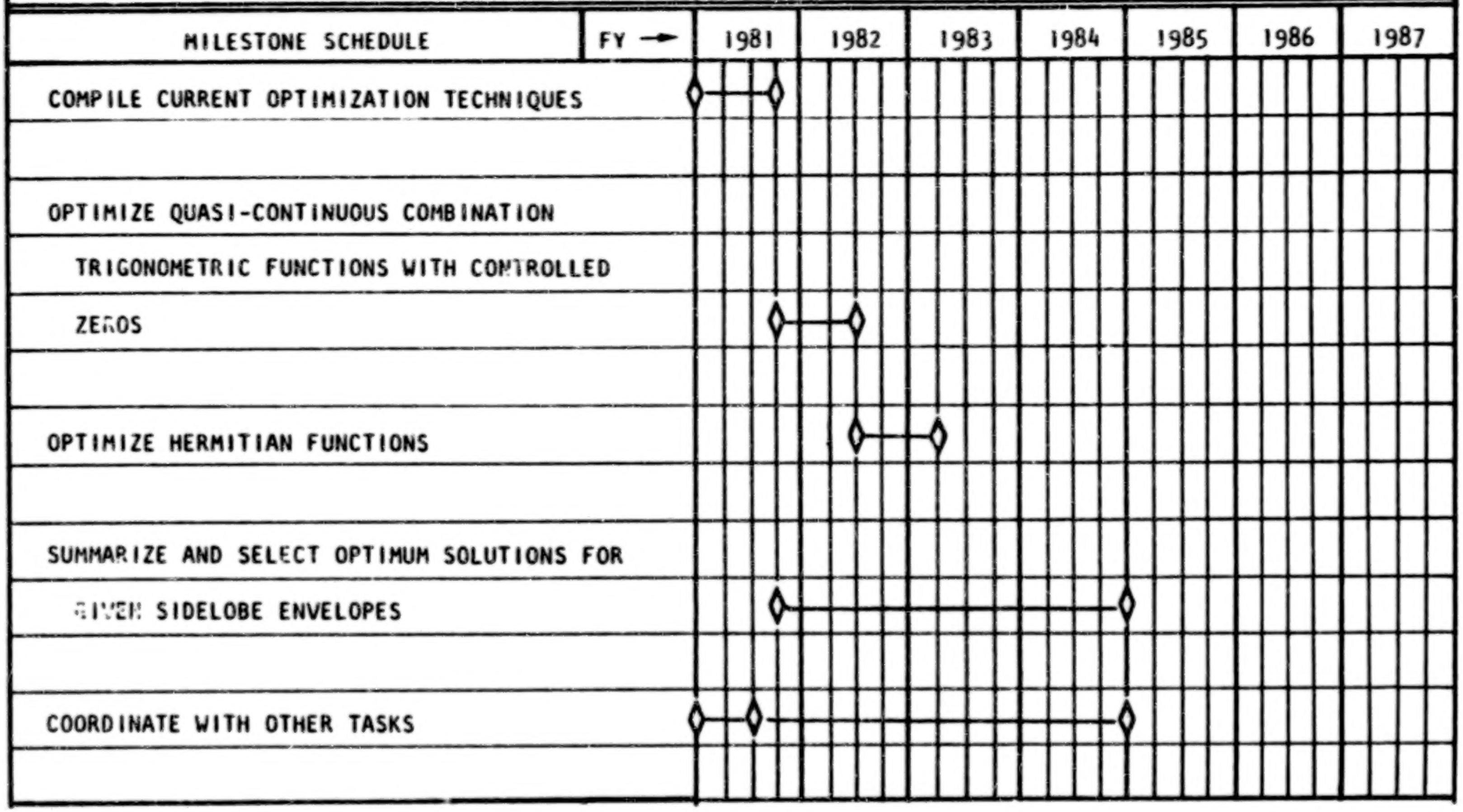
To construct distributions which optimize beam efficiency subject to given constraints on distribution edge pedestal and on sidelobe envelope.

APPROACH

Superpositions of various orders of combination cosine and cosine squared, both including pedestal will be investigated. Another approach can be formulated as the ratio of two quadratic hermitian forms. In both cases exact solutions can be calculated.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: APERTURE DISTRIBUTIONS



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TECHNOLOGY TITLE: STRUCTURES, CONTROLS, AND MATERIALS

TECHNICAL SUMMARY

The objective of this experimental research is to develop technology associated with specific aspects of the structural subsystem of an SPS (Satellite Power System). Optimum structural element shapes will be developed based on design, analysis and test data. Advanced composite material systems will be selected for SPS structures, applications and mechanical properties of those systems will be developed. (Mathematical simulations of SPS configurations, utilizing test determined stiffnesses, damping valves, etc., will be generated and subjected to simulated operational environments to determine "as designed" structural integrity including operational stress levels and satellite distortions.) SPS structure construction scenarios will be generated, construction equipment defined and conceptually designed, and a plan generated for the ground and on-orbit technology development of this equipment. (Attitude and figure control technology and ACS propulsion system research is also included in this effort.)

TASK SUMMARY

Structures and Materials

- Construction Selections and Structural Requirements - The objective of this effort is to determine the most suitable construction and definitive structural requirements to provide visibility and bounds for machine-made beam and beam-to-beam joining developments.

- Composite Materials Development - The objective of this effort is to develop a composite material of zero to negligible coefficient of expansion ($0.18\ 10^{-}$ m/m°C) that will maintain its structurally significant design properties (strength, stiffness) during 30-year exposure to stress and the space environment cyclic temperatures, and the vacuum and radiation environment.

- Machine-Made Beam Development - The objective of this effort is to develop, utilizing the selected composite material, two machine-made beam designs. The development is to proceed to the stage of ground fabrication and ground structural testing of a machine-fabricated design. The machine need not be a flight weight article.

- Beam-To-Beam Joining - The objective of this effort is to develop the best structurally suitable/low-cost/inspectable and repairable structural attachment for the joining of the developed machine-made beams.

- Ultra-Large Solar Blanket/Reflector Arrays - The objective of this effort is to develop the techniques of packaging, on-orbit controlled unfurling, and tensioning of solar blanket and reflector surfaces.

- Solid-State Sandwich Design - The objective of this effort is to develop a lightweight, ground-fabricated solid-state sandwich structural design compatible with electronic and thermal requirements.

- Mathematical Model Development - The objective of this effort is to extend current finite-element modeling techniques to permit rapid and economical, yet detailed, analysis of large space structures; and also to provide the capability of explicit definition of tension loads in cables.

Controls

- Ion Thruster and Power Module Laboratory Testing - The objective of this effort is to design a thruster subsystem that meets the characteristics defined by SPS mission analysis. The design is to include a practical means for replacing thruster grids using manipulator arms. The thruster system will provide two functions—Controls and Transportation. On orbit controls require that the thrusting policy approximate linear torques, including throttling plus on-off switching of the thrusters. Transportation requirements will be found in the Transportation Technology Area.

- EOTV Attitude and Thrust Vector Control - The objectives of this effort is to develop an integrated control system concept that provides both attitude control and thrust vector control, define the thruster configuration satisfying plume impingement constraints, and define optimal steering laws for EOTV orbit transfer.

- Figure Control Techniques and Systems - The selection of the figure control subsystem is the result of cooperative inputs between structures, materials, and control systems. The defined structural configuration will establish the requirements for displacement sensors, actuators, and software necessary for maintenance of the structural figure. The objective of this effort is to investigate and develop techniques and methodology for maintaining controls and make recommendations and provide requirements to the structural designer.

- Control System Development and Hardware Requirements - No experience exists which deals with the problems associated with on-orbit construction of large structures. Consequently computer simulations and associated software development must be accomplished in order to establish control systems and their hardware requirements. Control systems must be defined for all phases of construction as well as on-orbit operations. The objective of this effort is to define preferred control system software techniques, which will minimize undesirable dynamic interactions. Flight testing of systems which cannot be acceptably defined must occur in the post GBED period.

- ACS Electric Propulsion Development - The RCS system of the SPS will utilize the EOTV for stationkeeping and attitude control. The objective of this effort is to define both an EOTV and RCS system which are mutually compatible with each other, and to confirm their performance and lifetime characteristics with ground based testing.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: CONSTRUCTION SELECTIONS AND STRUCTURAL REQUIREMENTS

JUSTIFICATION

SPS structural configurations can utilize tri-beam structures comprised of machine-made beams in numerous arrangements. For example, either a pentahedral truss employing machine-made beams joined by appropriate unions, or machine-made beams stabilized by a system of X-bracing comprised of pretensioned cable can be used. There are, of course, other constructions. The most suitable construction (or constructions) to satisfy the design requirements for the SPS structural configuration has not been established. Establishment of the most suitable constructions necessary for visability and bounding of requirements for machine-made beams and joint development is required for the development programs contained herein.

TECHNICAL OBJECTIVE

To determine the most suitable construction and definitive structural requirements to provide visibility and bounds for machine-made beam and beam-to-beam joining developments.

TECHNICAL APPROACH

(1) Establish overall system induced structural requirements and configurations for the diverse classes of structure such as microwave antennas, solar blanket support structures, and primary reflector support structures.

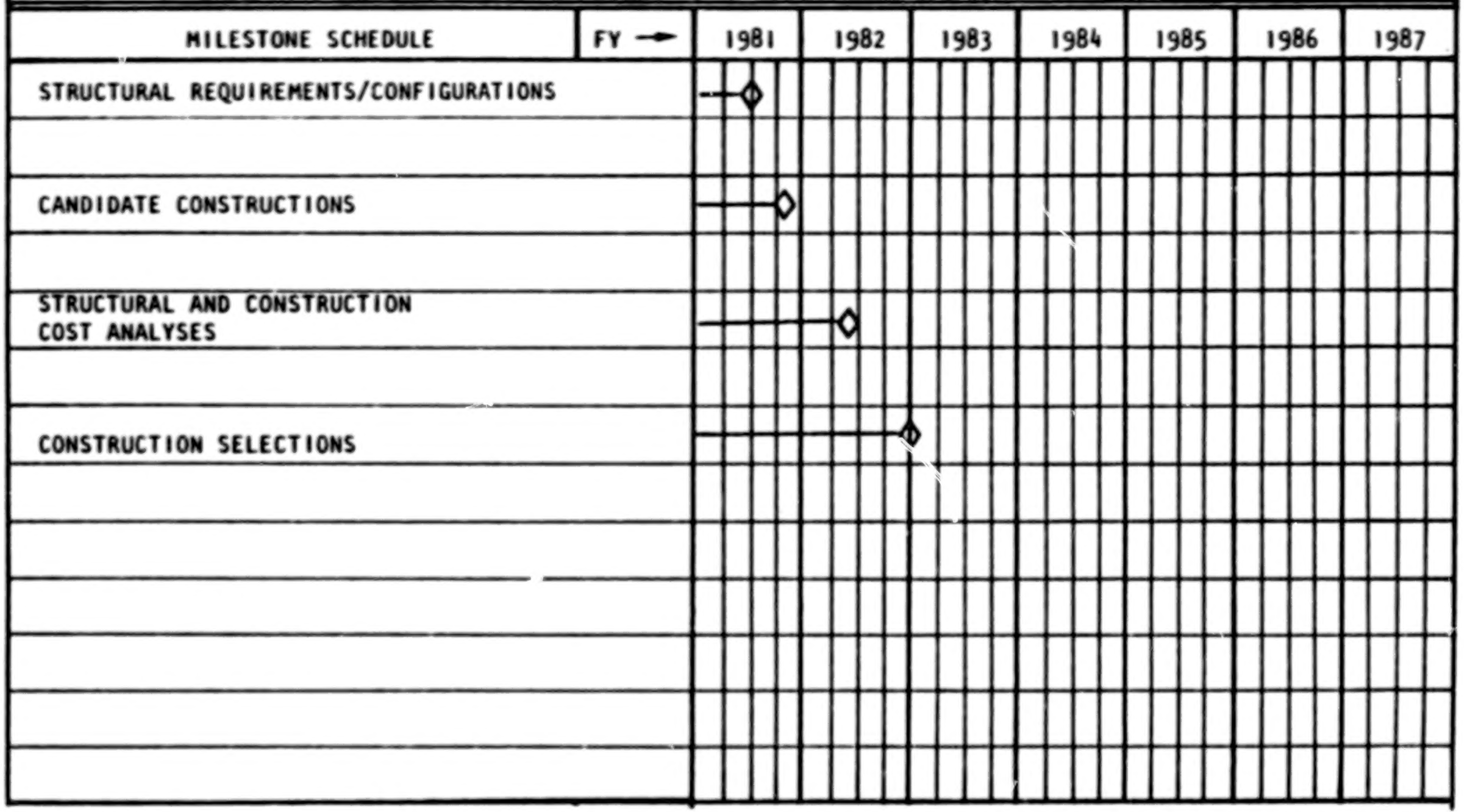
(2) Establish candidate constructions.

(3) Perform structural and construction cost analyses.

(4) Select most suitable constructions for each item of structure.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: CONSTRUCTION SELECTIONS AND STRUCTURAL REQUIREMENTS



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: COMPOSITE MATERIALS DEVELOPMENT

JUSTIFICATION

Advanced composite structural materials of zero to negligible (0.18×10^{-6} m/m°C) coefficient of expansion have superior performance characteristics to those of metallic structures. Such composites can satisfy stringent MPTS figure control requirements without active control, but in addition, experience negligible construction and operation induced thermal loads compared to those of metallics. The higher stiffness to density characteristics and the foregoing result in less structure weight. However, the specifics of the actual composite material design for compatibility with beam machine fabrication and for long-term (30-year) structural suitability require development.

TECHNICAL OBJECTIVE

Develop a composite material of zero to negligible coefficient of expansion (0.18×10^{-6} m/m°C) that will maintain its structurally significant design properties (strength, stiffness) during 30-year exposure to stress and the space environment cyclic temperatures, and the vacuum and radiation environment.

TECHNICAL APPROACH

This task will be conducted as follows:

(1) Determine design requirements for composite materials.

(2) Apply composite material technology to define candidate composite materials that satisfy requirements.

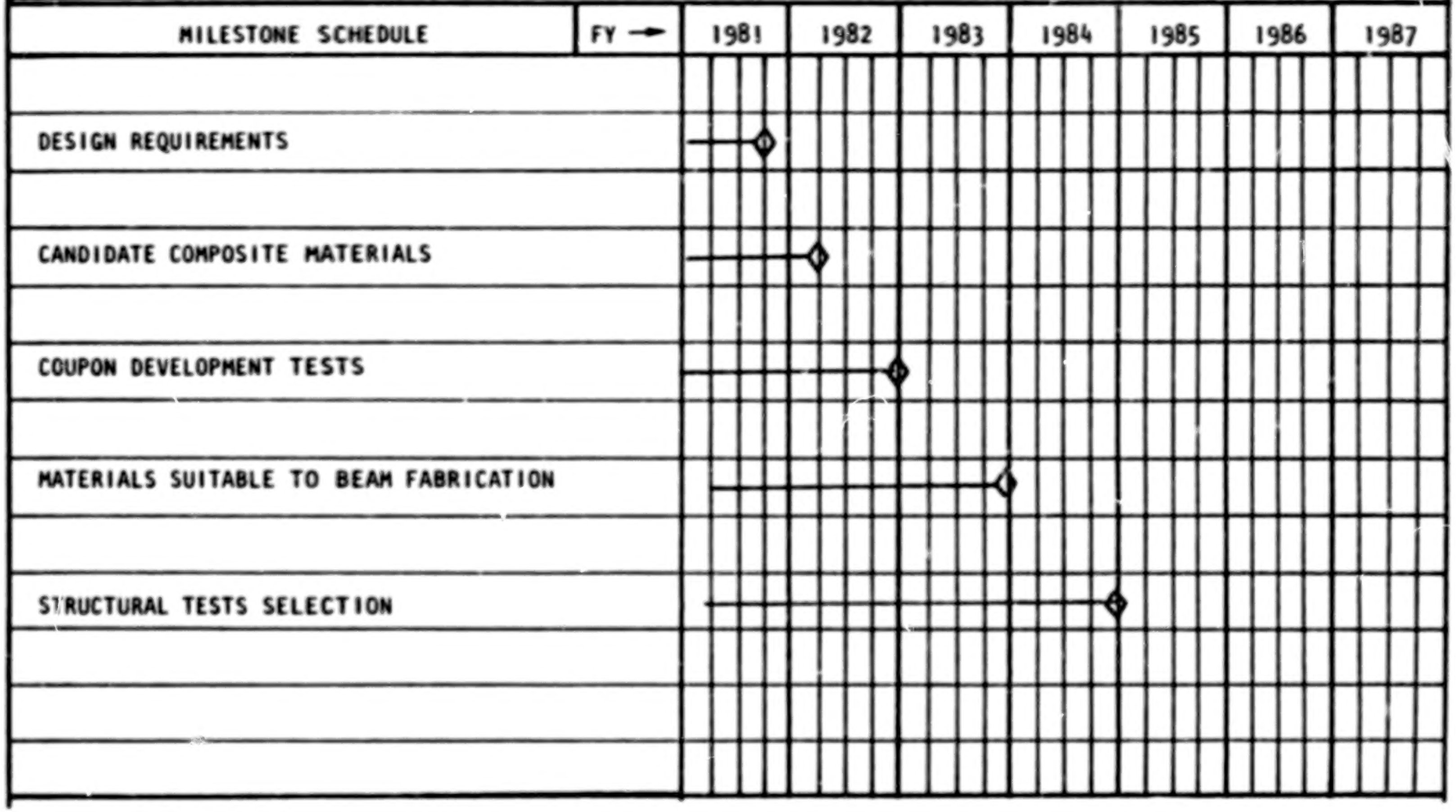
(3) Perform coupon development tests to verify suitability of candidate designs. The tests will determine strength, stiffness, coefficient of expansion before and after accelerated exposure to environments.

(4) From acceptable materials, determine most suitable materials for fabrication and attachment capability.

(5) Verify material selection by fabrication of cap and appropriate structural tests.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: COMPOSITE MATERIALS DEVELOPMENT



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MACHINE-MADE BEAM DEVELOPMENT

JUSTIFICATION

Critical to an SPS or any large space structure is the development of the machine-made beam. Expecting minimum SPS structural weight to be compatible with minimum system cost, minimum weight requires structural optimization of the machine-made beam. Minimum weight will also require at least two different optimized machine-made beam designs. The higher loaded beams will certainly utilize closed-cap designs, while the lightly loaded structures may use either closed or open section caps. In either design the three caps will be arranged to form a prismatic beam of equilateral triangular cross-sections, joined together by an appropriate system of cross and diagonal members. The design optimization must also recognize the subsequent load and construction requirements for attachment between the beams, and appropriate quality assurance inspection techniques. Finally, the quality assurance techniques for the basic machine-made beam fabrication must also be developed.

TECHNICAL OBJECTIVE

Develop, utilizing the selected composite material, two machine-made beam designs. The development is to proceed to the stage of ground fabrication and ground structural testing of a machine-fabricated design. The machine need not be a flight weight article.

TECHNICAL APPROACH

The foregoing objectives will be accomplished as follows:

(1) Conduct survey of SPS system definition studies to define the machine-made beam load requirements, effective unsupported length, and other significant design requirements.

(2) Perform structural optimization/fabrication feasibility studies to define the most suitable beam design.

(3) Verify structural suitability of beam designs by fabrication and structural testing of beam designs.

(4) With verification, proceed to design and fabricate two ground demonstration beam machines. Design of machines shall permit variation of material cap gauges.

(5) Use ground demonstration machines to fabricate the two beams and perform appropriate structural tests.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MACHINE-MADE BEAM DEVELOPMENT

MILESTONE SCHEDULE	FY → 1981	1982	1983	1984	1985	1986	1987
BEAM REQUIREMENTS		◇					
STRUCTURAL OPTIMIZATION/FABRICATION FEASIBILITY			◇				
STRUCTURAL TESTS OF DESIGN				◇			
DESIGN/FABRICATE GROUND DEMONSTRATION MACHINE					◇		
STRUCTURAL TEST OF FINAL BEAM						◇	

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: BEAM-TO-BEAM JOINING

JUSTIFICATION

The method of joining machine-made beams is critical not only to structural suitability, but to the cost of construction. The methods of attachment can use concentric or lap joints, fixed or pinned joints, and welding or mechanical attachment. Critical to minimum weight, the joint design must be structurally suitable within the capability of the basic beam design, i.e., the joint loads shall not require increase of the basic beam gauges. The joint must also be of such a design that produces not space debris, and is readily inspectable and repairable.

TECHNICAL OBJECTIVE

To develop the best structurally suitable/low-cost/inspectable and repairable structural attachment for the joining of the developed machine-made beams.

TECHNICAL APPROACH

(1) Extract from the construction selection and structural requirements development, the regimes of loads imposed and most suitable joint configuration.

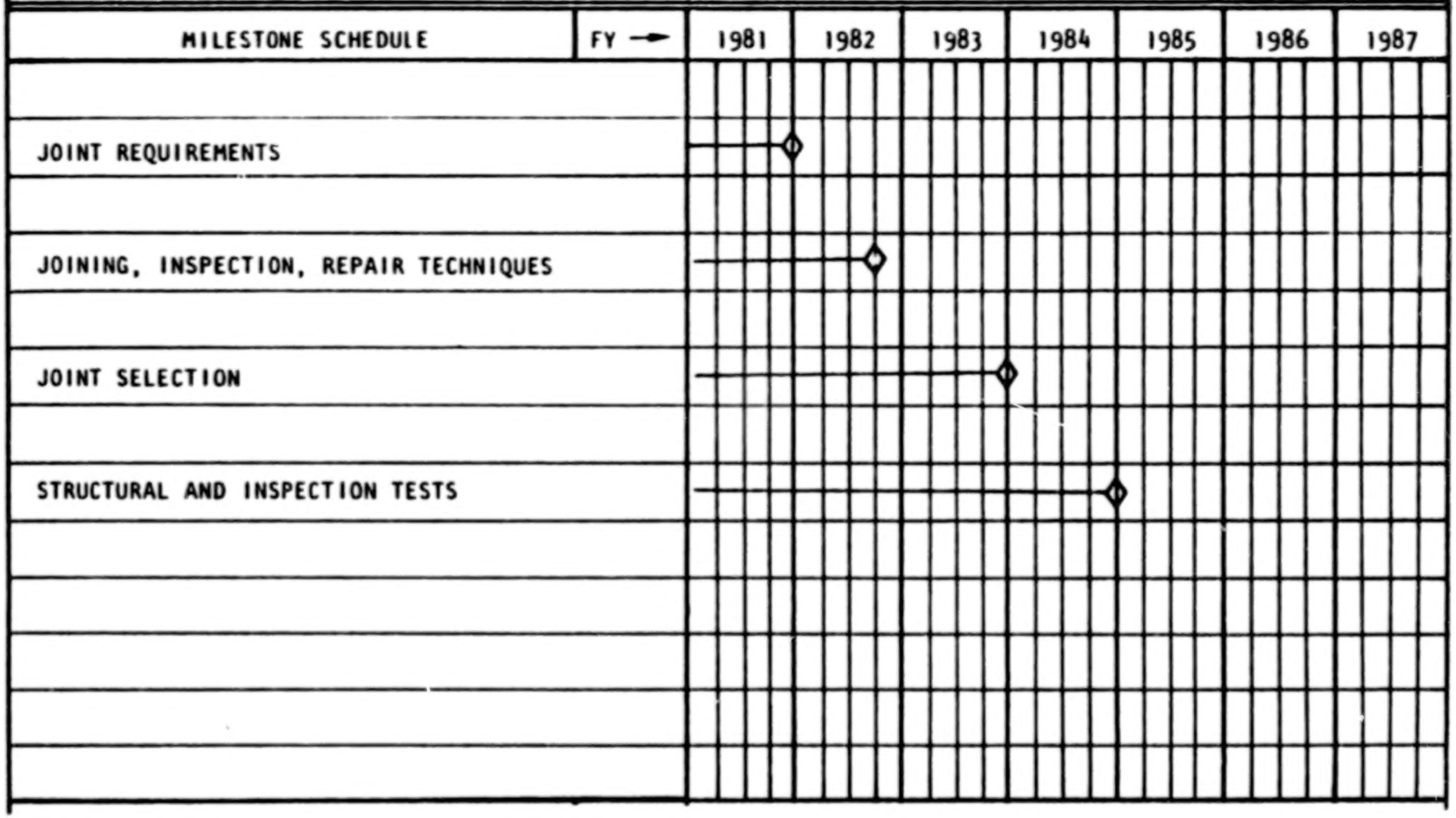
(2) Develop joining, inspection, and repair techniques.

(3) Study and select the most suitable joint.

(4) Perform structural load tests, inspection tests, and demonstrate repair capability.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: BEAM-TO-BEAM JOINING



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ULTRA-LARGE SOLAR BLANKET/REFLECTOR ARRAYS

JUSTIFICATION

The solar blanket and reflector surfaces are stabilized by tension cable systems, having no rigidity of their own. In view of the large areas, these surfaces will be built up from numerous parallel strips to be subsequently joined together. The strips, in particular those of the reflectors, are comprise of 1/2-mil kapton which will subsequently have to accommodate attachment of the tension cables. The techniques for packaging, controlled on-orbit unfurling, strip-to-strip joining, structural attachment of cables, appropriate tensioning are not available.

TECHNICAL OBJECTIVE

To develop the techniques of packaging, on-orbit controlled unfurling, and tensioning of solar blanket and reflector surfaces.

TECHNICAL APPROACH

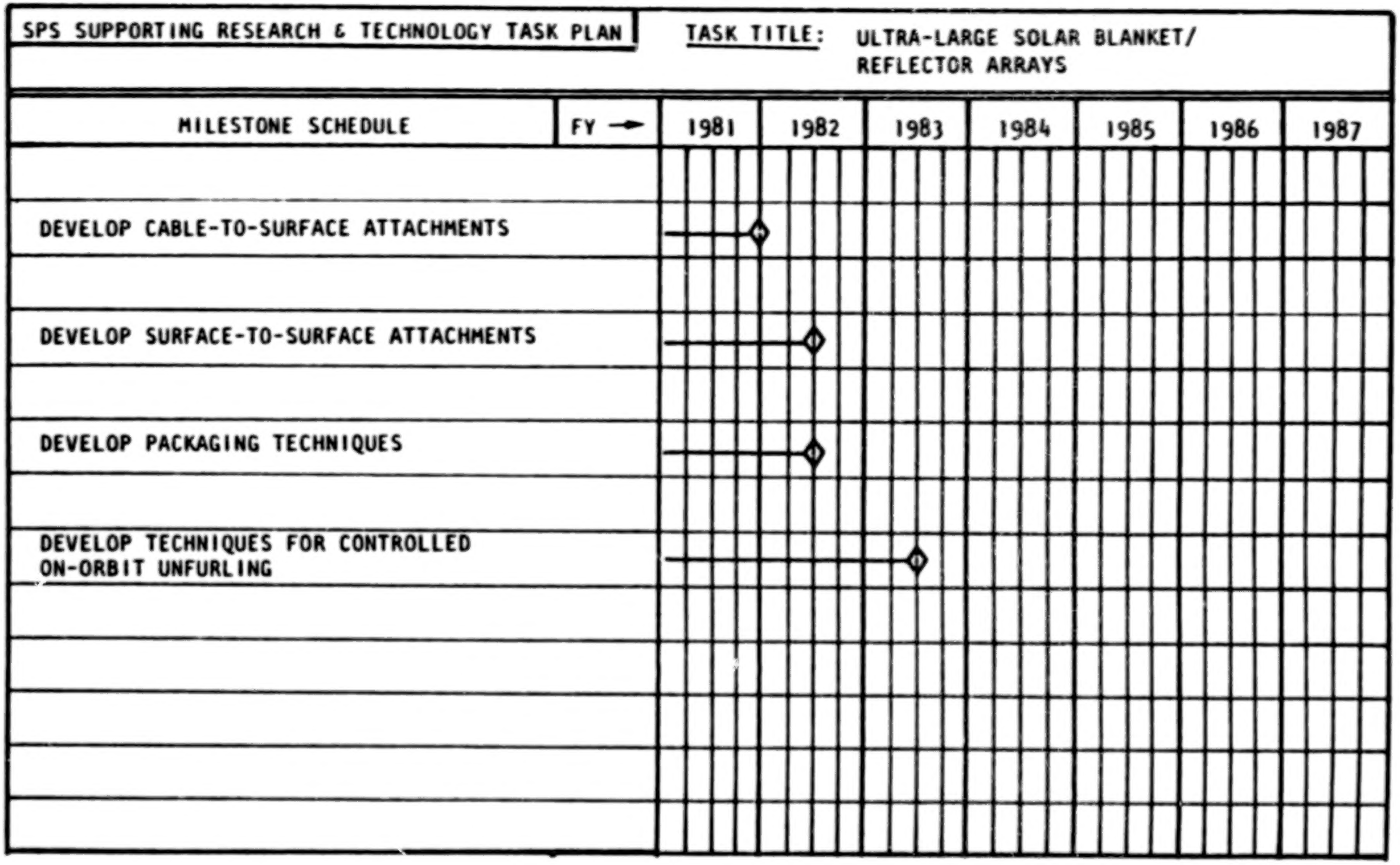
The foregoing objective will be accomplished as follows:

(1) Develop cable-to-surface attachment techniques.

(2) Develop surface-to-surface attachment techniques.

(3) Develop packaging techniques.

(4) Develop techniques for controlled on-orbit unfuling, strip attachment, cable attachment.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: ULTRA-LARGE SOLAR BLANKET/ REFLECTOR ARRAYS
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
DEVELOP CABLE-TO-SURFACE ATTACHMENTS
DEVELOP SURFACE-TO-SURFACE ATTACHMENTS
DEVELOP PACKAGING TECHNIQUES
DEVELOP TECHNIQUES FOR CONTROLLED ON-ORBIT UNFURLING

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: SOLID-STATE SANDWICH DESIGN

JUSTIFICATION

Solid-state electronics for the MPTS is attractive in that the extensive power transmission conductor runs and power transfer across a rotary joint are eliminated. Yet, the solid-state sandwich design presents a significant structural design challenge. The structural design must be lightweight (1 to 2 kg/m^2) and, in view of the design complexity, be fabricated on the ground, survive the launch dynamic environment, utilize dielectric materials, passively limit solar cell temperatures to no more than 200°C, and maintain flatness comparable with electronic requirements. Satisfaction of these requirements with a reliable, fabricable structure will require extensive development.

TECHNICAL OBJECTIVE

To develop a lightweight, ground-fabricated solid-state sandwich structural design compatible with electronic and thermal requirements.

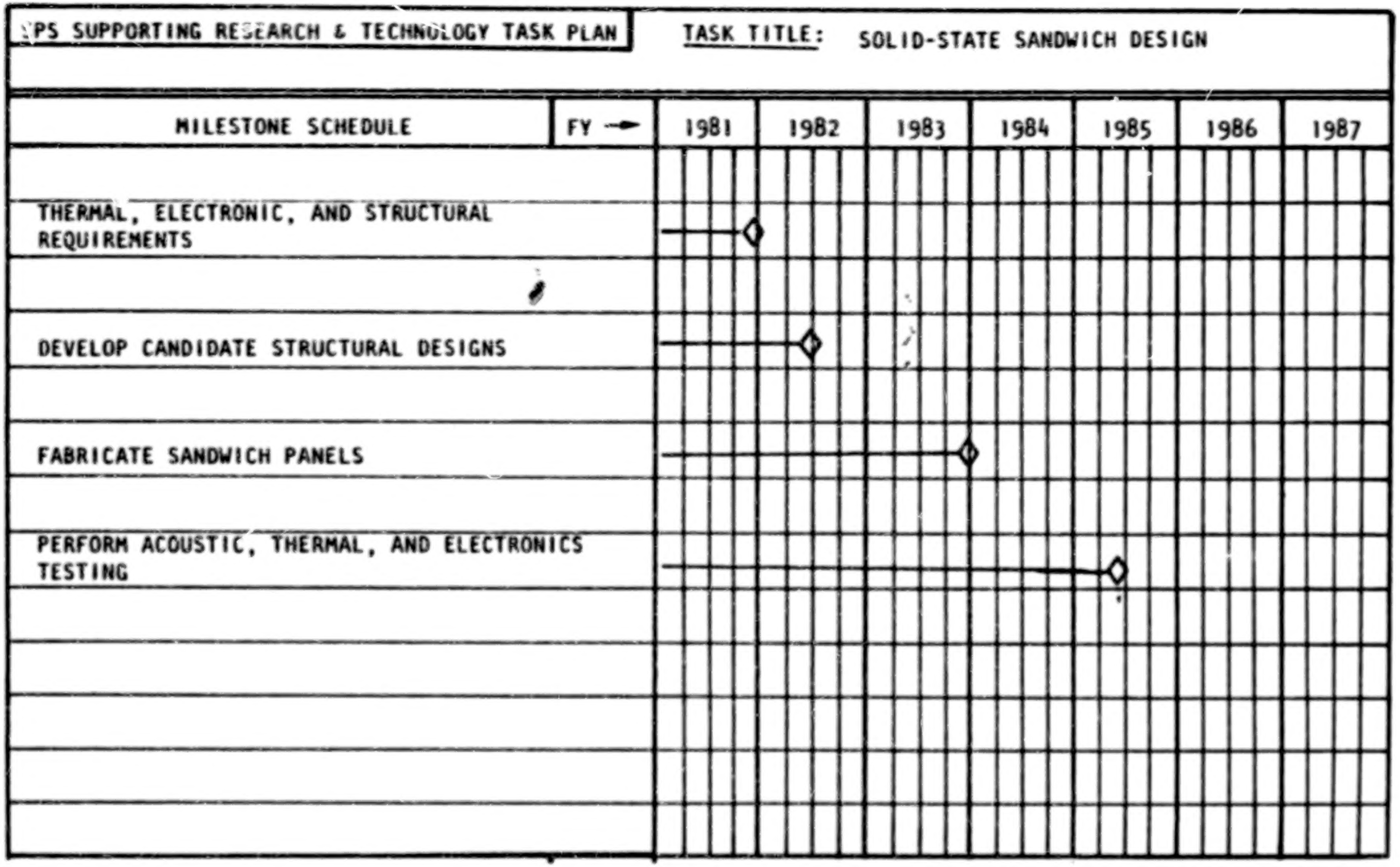
TECHNICAL APPROACH

(1) Establish thermal, electronic, and structural requirements.

(2) Develop structural designs to satisfy requirements.

(3) Fabricate sandwich panels.

(4) Perform acoustic, thermal, and electronic testing to verify design.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: SOLID-STATE SANDWICH DESIGN
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
THERMAL, ELECTRONIC, AND STRUCTURAL REQUIREMENTS
DEVELOP CANDIDATE STRUCTURAL DESIGNS
FABRICATE SANDWICH PANELS
PERFORM ACOUSTIC, THERMAL, AND ELECTRONICS TESTING

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MATHEMATICAL MODEL DEVELOPMENT

JUSTIFICATION

The qualification of SPS structures will be based on structural and dynamic analyses that utilize large detailed fine-element models for prediction of structural behavior. The structural characteristics used in these models will be determined from appropriate development tests of joints and subassemblies. However, present finite-element modeling techniques have significant deficiencies for use in large space structures analyses. The multiple tiers of structural systems require monstrous finite-element models to predict structural performance. Conceptual trade analysis and configuration design development require the prediction of the behavior of relatively detailed structure. The smeared-beam models presently used for trade studies do not allow an adequate representation of the influence of local truss geometry. Also, structures using tension cable arrays will be tensioned to prescribed values. An explicit method of inducing prescribed tension values is not available.

TECHNICAL OBJECTIVE

To extend current finite-element modeling techniques to permit rapid and economical, yet detailed, analysis of large space structures; and also to provide the capability of explicit definition of tension loads in cables.

TECHNICAL APPROACH

The foregoing objectives will be achieved by:

(1) Development of low-cost, simplified, modeling techniques.

(2) Extension of finite-element techniques to accommodate prescribed specified tension loads.

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SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MATHEMATICAL MODEL DEVELOPMENT

MILESTONE SCHEDULE	FY → 1981	1982	1983	1984	1985	1986	1987
LOW-COST SIMPLIFIED MODELING TECHNIQUES							
EXTENSION OF FINITE ELEMENT TECHNIQUES							

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ION THRUSTER AND POWER MODULE LABORATORY TESTING

JUSTIFICATION

The EOTV argon ion propulsion system can only operate efficiently (competitively and advantageously) if refurbishment requirements can be minimized. It appears from work done at LeRC that thruster modules can be designed that will operate for decades without excessive deterioration, or a need for refurbishment, except for the accelerating grid sets. The grids are subject to positive ion bombardment, etc., and will require periodic refurbishment. A major redesign of thruster modules is therefore required. This involves not only removable grid sets, but also possibly new materials, laboratory models, and supporting tests. To minimize vibration excitation, a thrusting policy is required that approximates linear torques. The approximation of linear torques is produced by a quasi-linear thrusting policy that includes the throttling plus on-off switching of the thrusters. The investigation and development of throttling techniques should be pursued.

TECHNICAL OBJECTIVES

- Complete a EOTV mission analysis that reveals the set of desired thruster operating characteristics: i.e., special impulse, thrust, trip time, fleet size, payload, electric power profiles, and refurbishment cycles.
- Conceptually design and size thrusters that satisfy the required thruster characteristics of the mission analysis.
- Design and verify, with a simulated arrangement, a practical means of replacing thruster grids (several at one time) with the use of manipulator arms or some other arrangement.
- Design and build a laboratory thruster module (one or more as required) which incorporates the refurbishable grid system selected from the simulated arrangement.
- Test the thruster module to establish thrust, beam divergence, effectiveness of beam neutralization, and grid deterioration rates, etc.

APPROACH

- It is the task of the mission analysts to determine the preferred set of thruster operating characteristics, i.e., accelerating voltage (specific impulse), beam current (thrust), trip times (LEO to GEO, GEO to LEO), refurbishment cycles, solar blanket BOL power, mean electrical output, annealing cycles and methods, payload per EOTV trip, number of HLLV launches per SPS in GEO, thruster lifetime, etc. It is necessary to study the gross scenario in order to determine minimum overall cost and to flatten cost peaks. A sensitivity study is also required to minimize program perturbations from material shortages or supply problems.

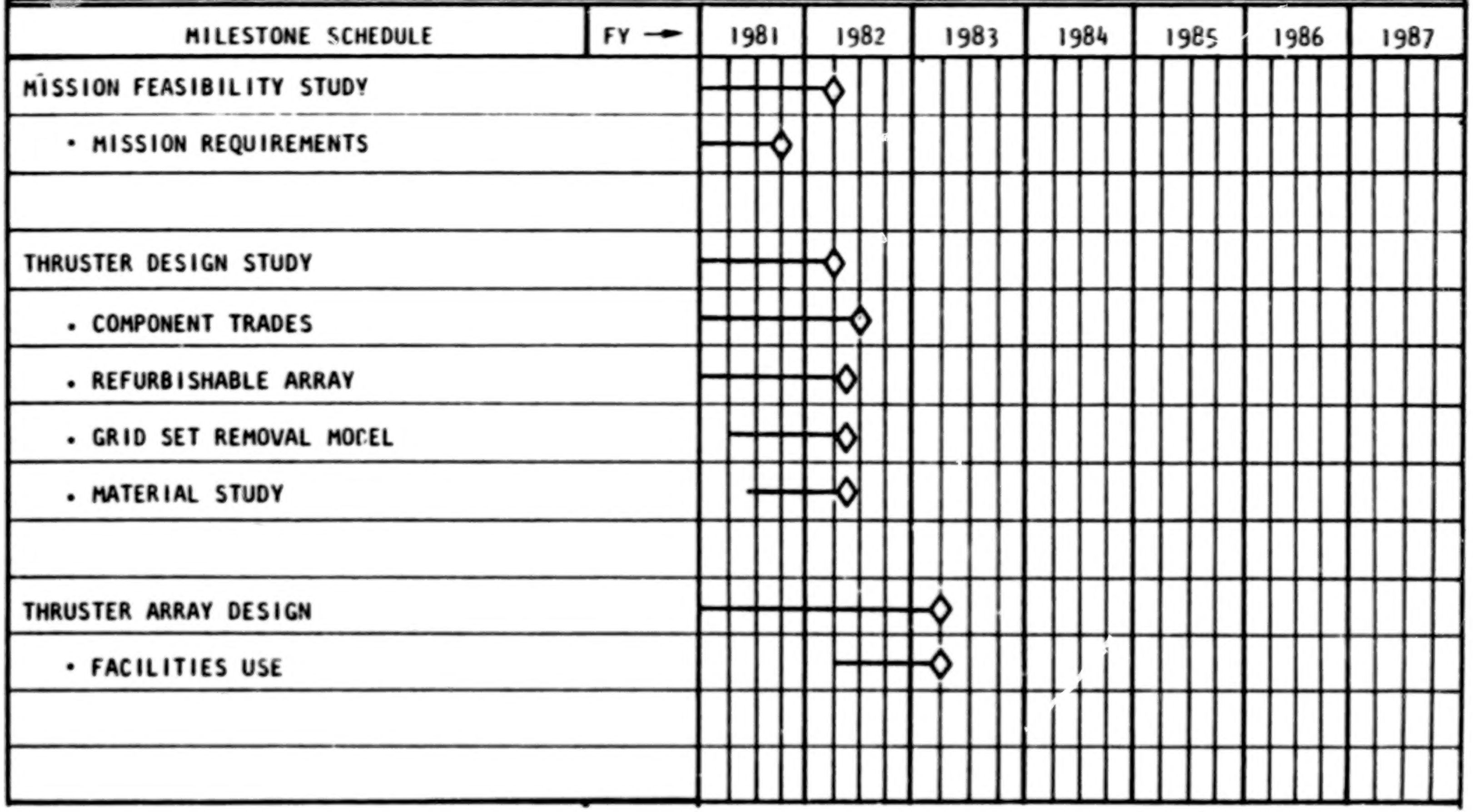
- The conceptual design and sizing will be carried out so as to overlap with the requirements (mission) analysis. It is anticipated that the facilities and expertise associated with LeRC will be employed.

- It is required that the grids be removable from the front. For example, each grid might be held in place by a compressed spring much like a bayonet light bulb. In this case a simulated manipulator would push the grid in axially, twist it 90°, and then pull it out. This task therefore must examine the problem of grid refurbishment, i.e., replacing the expended grid with a new or refurbished grid. Preferably an entire group of grids should be replaced as a unit.

- It is anticipated that the construction and testing of an actual thruster will be done at LeRC. Verification of thrust, beam divergency, neutralization effectiveness, etc., are typical measurements that would be desirable. A pendulum arrangement for estimating thrust is available at LeRC.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ION THRUSTER AND POWER MODULE LABORATORY TESTING



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: EOTV ATTITUDE AND THRUST VECTOR CONTROL

TECHNOLOGY REQUIREMENT

The SPS study recommended a GEO construction using an electrical orbital transfer vehicle (EOTV) for cargo transportation between LEO and GEO. In the orbit transfer the pointing of the solar collector is required to minimize the power loss and an optimum or sub-optimum steering history is required to minimize propellant consumption. An integrated control system satisfying the plume impingement constraints for attitude control and thrust vector control (TVC) should be designed and developed to accomplish a cost effective orbit transfer.

TECHNICAL OBJECTIVE

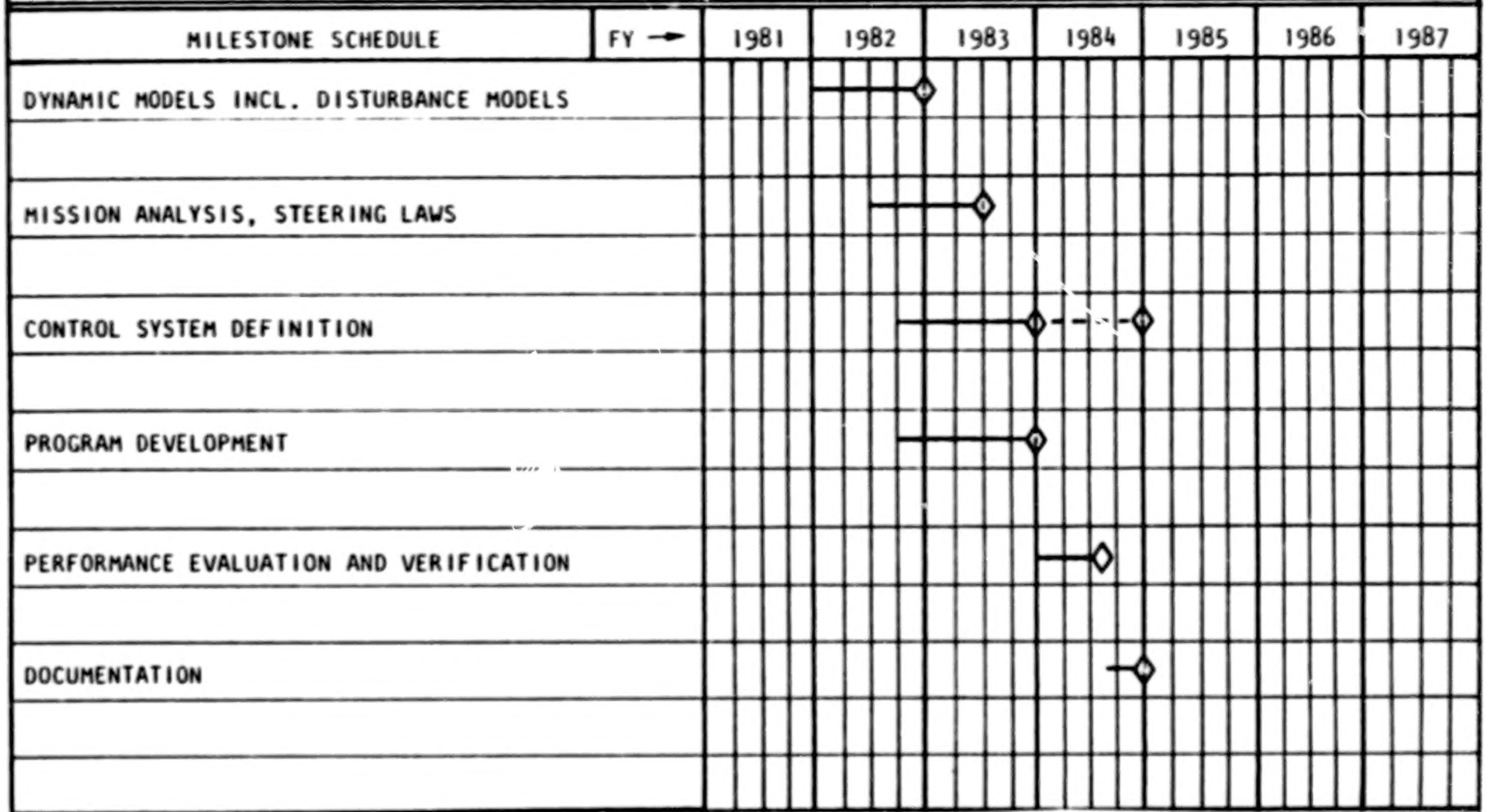
Define integrated control system concepts that provide attitude control and TVC; define thruster configurations to provide the maximum flexibility for TVC and attitude control and satisfy plume impingement constraints; define optimum or sub-optimal steering law for EOTV orbit transfer; define preferred control systems.

TECHNICAL APPROACH

Develop dynamic models for control system design including time varying disturbance models for aerodynamic drag, gravity-gradient torques, and solar pressure forces and torques; perform mission analysis to include the investigation of preferred launch geometry and the development optimum or sub-optimum steering laws; define control system concepts to include thruster configurations; sensors, control laws, etc.; develop digital computer simulators for performance evaluation and verification; define preferred control concepts for EOTV.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: EOTV ATTITUDE AND THRUST VECTOR CONTROL



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: FIGURE CONTROL TECHNIQUES AND SYSTEMS

TECHNOLOGY REQUIREMENT

The requirements for figure control increase rapidly as a function of concentration ratio (CR) of the solar collector. SPS concepts with higher CR's require more stringent figure accuracy. Higher CR's for the collectors are desirable to minimize the cost of solar cell blankets.

STATE OF THE ART

Figure control techniques have been explored including practical applications and theoretical results. Some of the concepts are a passive technique which includes the installation of local dampers in the spacecraft frame, a semi-passive thermally activated expansion joint, and an active technique which processes modal rate data to drive actuators for modal damping. However, there remains a considerable research and development in this area.

TECHNICAL OBJECTIVES

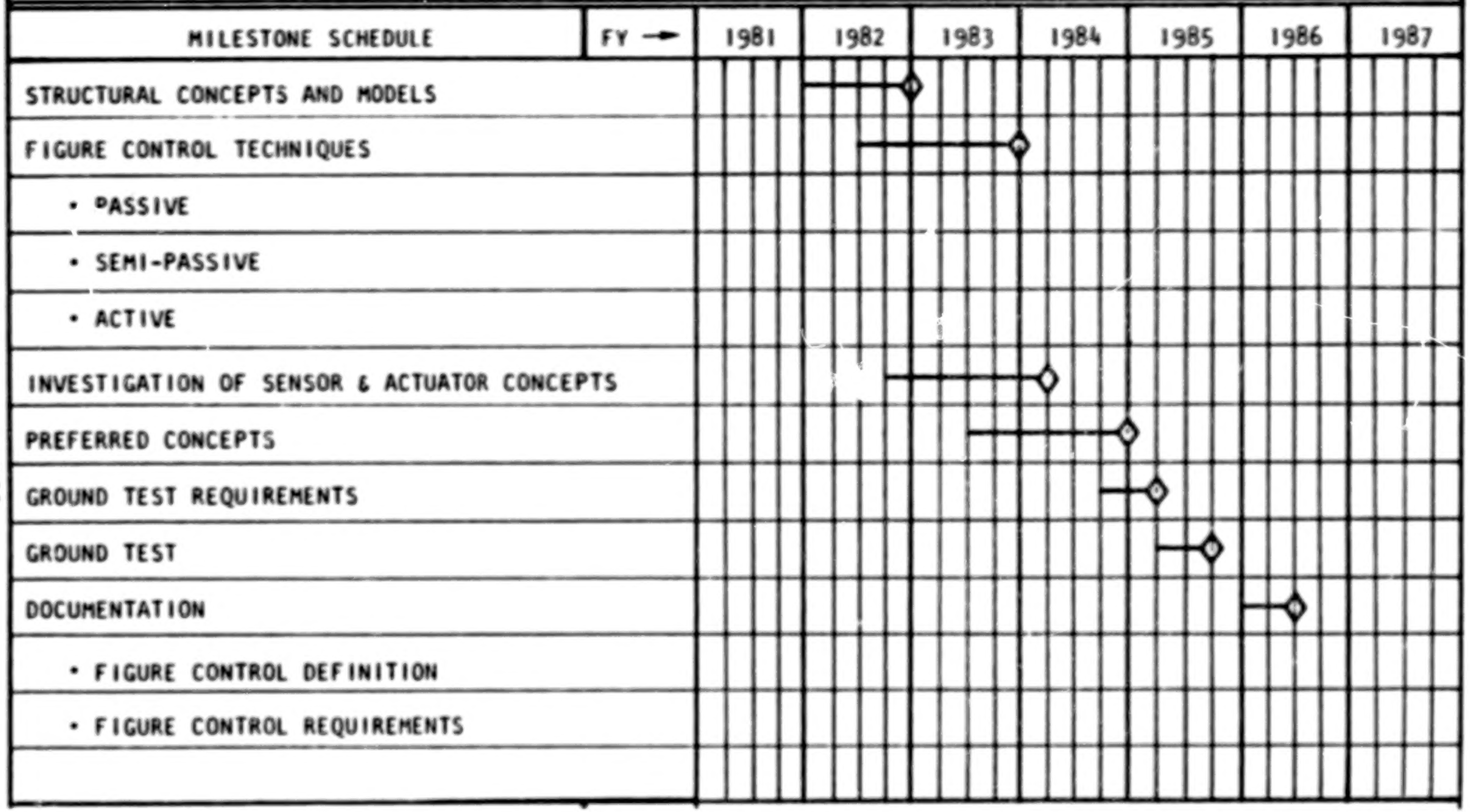
Define preferred structural concepts; define preferred techniques, compare active and passive control; define design criteria for vibration control; define rationale for selecting the number and locations of structural actuators. Define the relative merits of new figure control actuators and compare with contemporary electromechanical actuators. Refine preferred approaches for SPS.

TECHNICAL APPROACH

Define active/passive techniques to minimize thermal and vibration deformation; and define alignment techniques to minimize assembly misalignment. Define preferred number and locations for structural actuators, requirements and achievable alignment accuracies. Investigate the design and achievable performance with new figure control actuator concepts such as the semi-passive thermally controlled expansion joint. Define the preferred structure and figure control concepts for SPS. Define requirements for ground testing verification and perform ground test to confirm design.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: FIGURE CONTROL TECHNIQUES AND SYSTEMS



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: CONTROL SYSTEM DEVELOPMENT AND HARDWARE REQUIREMENTS

TECHNOLOGY REQUIREMENT

Traditionally the achievement of satisfactory control system/structural dynamics performance and stability has been achieved through the use of analytical and ground testing techniques to confirm modeling assumptions and uncertainties. With extremely large, lightweight and flexible SPS structure full scale testing is precluded. Thus, a greater burden must be placed upon analytical methods in the design.

STATE OF THE ART

In contemporary spacecraft design control system/structural dynamics interaction is important but a secondary consideration. This interaction for large structures may be the dominant design consideration. These large structures will potentially be very high dimensional systems and the present systems which are of limited dimensionality often extend the capabilities of the available analytical and simulation design tools.

TECHNICAL OBJECTIVES

Define and evaluate control systems designs for large, lightweight SPS for all mission phases from assembly through operational orbit. Define structural dynamics model for control system analyses and design; develop automated computer tools for control system analyses, design and verification, and define preferred control system software techniques to minimize undesirable dynamic interaction and flight test requirements to confirm the modeling and control concepts.

TECHNICAL APPROACH

Investigate the requirements for new structural dynamics modeling techniques and preferred approaches for control system analysis and design; new disturbance models are included which are appropriate to SPS (gravity-gradient and thermal bending disturbance). Develop automated control system/structural dynamics analysis programs appropriate for these higher order systems. Investigate the application of modern control theory to minimize structural dynamic interaction. Define the requirements for verification for ground test and ground test to confirm control system concepts.

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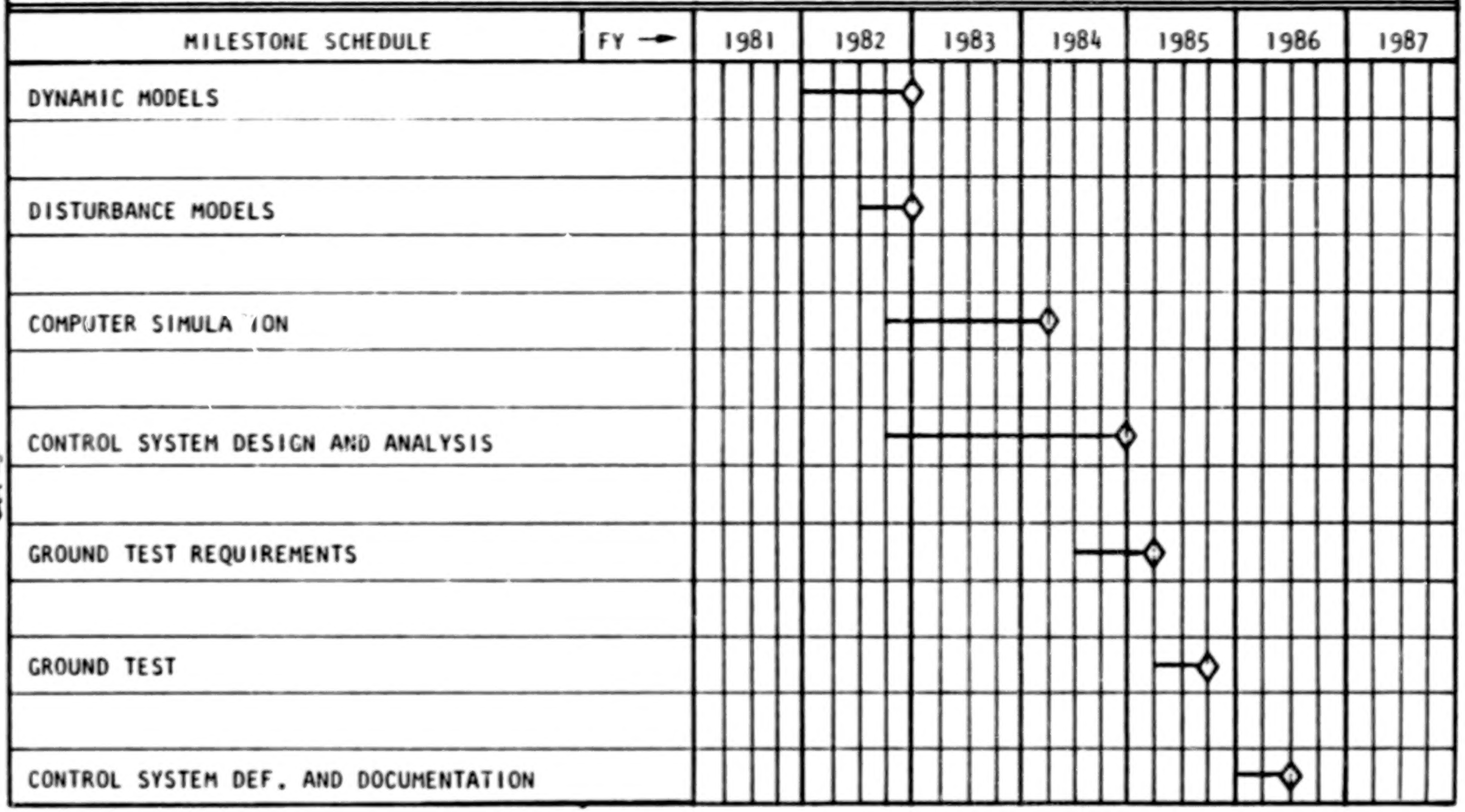
SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: CONTROL SYSTEM DEVELOPMENT AND HARDWARE REQUIREMENTS



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ACS ELECTRIC PROPULSION DEVELOPMENT

JUSTIFICATION

The 1976 and 1977 SPS study effort clearly established the desirability of high performance ($I_{sp} \cong 13,000—30,000$ sec), long life, low cost electric propulsion for use in the SPS Attitude Control and Stationkeeping Subsystem (ACS) and for the Electric Orbit Transfer Vehicle (EOTV).

- Performance - The high performance electric propulsion for the EOTV was found to result in very substantial cost savings relative to a chemical OTV. For the SPS spacecraft the stationkeeping and attitude control functions were found to require high performance propulsion in order to prevent very large propellant resupply costs over the satellite lifetime.
- Thruster Life - The currently estimated argon ion thruster lifetime of 5000 operating hours will result in large cost penalties for thruster replacement and/or refurbishment for SPS S/C. Techniques to extend the lifetime of the thruster grids so as to minimize the overall cost (initial plus servicing) should be pursued.
- Propellant Trades - Because of the desirability of high I_{sp} propulsion systems, various propellants should be investigated to determine optimum thruster system.
- Thruster Power Processing - Traditional electric thruster power processing electronics are quite massive and expensive. Techniques to utilize relatively raw power from the solar arrays and simpler control electronics to satisfy the thrusting requirements of the SPS spacecraft application require further investigation in order to define reliable, low cost power processing techniques equipment.
- Cryogenic Propellant Storage - The storage of the argon propellant as a cryogen (rather than as a gas) will appreciably reduce tank mass and transportation costs for propellant delivery. The cryogenic propellant storage systems require further design analysis to define preferred design concepts.

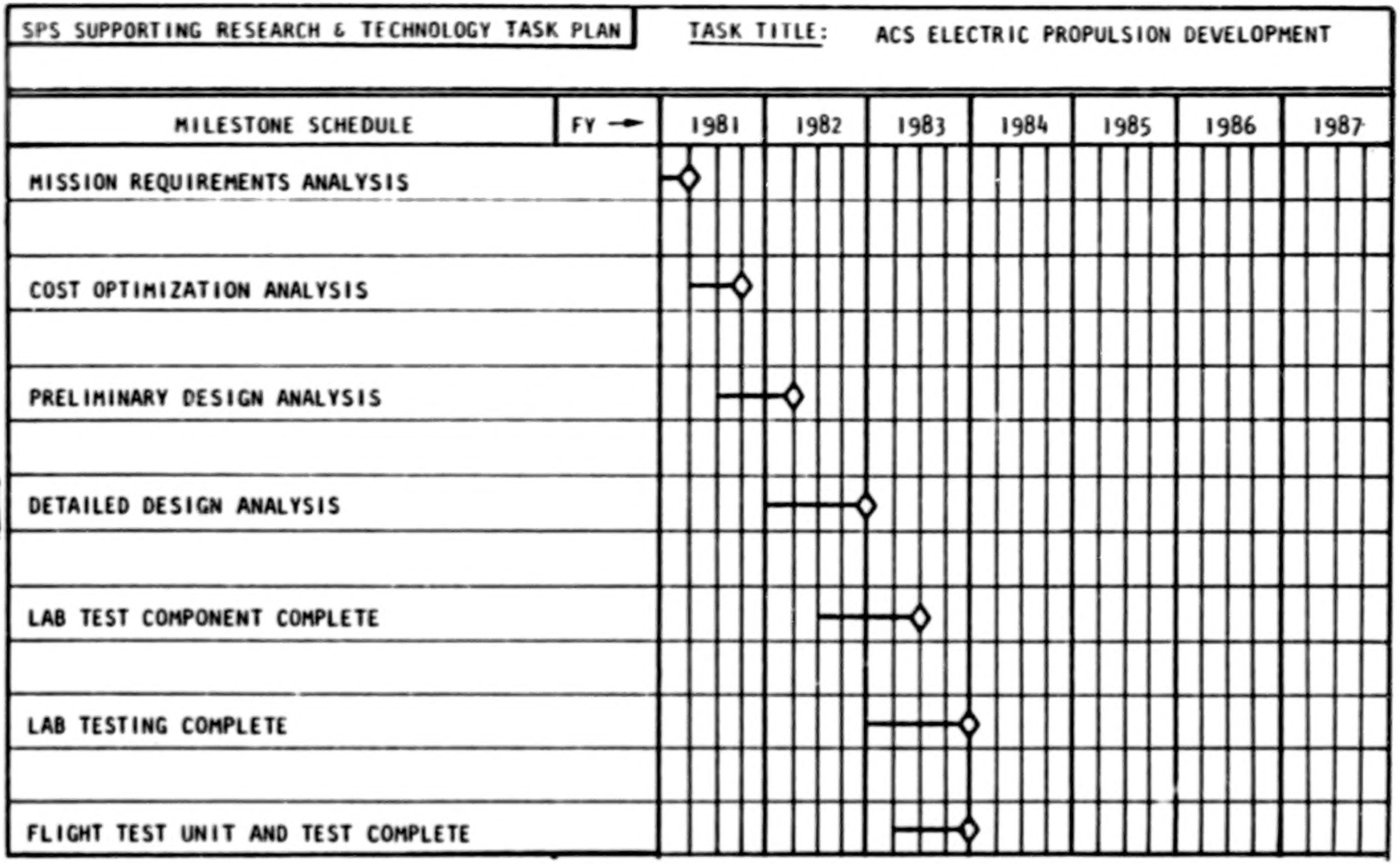
TECHNICAL OBJECTIVES

- Define thruster design parameters, servicing requirements, power processing techniques and propellant storage design techniques to minimize the overall electric propulsion subsystem costs (hardware plus propellant resupply costs) for the EOTV and the SPS satellite RCS.
- Confirm the performance and lifetime characteristics of the electric thrusters with ground based testing.

- Develop a flight demonstration thruster for flight verification of performance and lifetimes.

APPROACH

- Perform mission requirements analyses and cost optimization studies to define the most cost effective thruster subsystem design parameters.
- Perform preliminary and detailed thruster designs for ground and flight verification tests.
- Perform ground and flight tests to confirm the thruster performance and lifetime characteristics.


SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN
TASK TITLE: ACS ELECTRIC PROPULSION DEVELOPMENT
MILESTONE SCHEDULE
FY →
1981
1982
1983
1984
1985
1986
1987
MISSION REQUIREMENTS ANALYSIS
COST OPTIMIZATION ANALYSIS
PRELIMINARY DESIGN ANALYSIS
DETAILED DESIGN ANALYSIS
LAB TEST COMPONENT COMPLETE
LAB TESTING COMPLETE
FLIGHT TEST UNIT AND TEST COMPLETE

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TECHNOLOGY TITLE: SPACE OPERATIONS

TECHNICAL SUMMARY

The objective of this category is to acknowledge elements comprising Space Operations and to describe tasks associated with their completion during the period of 1981-1986. Developing the capability for construction and assembly of large low-density structures in space is an inherent requirement for the SPS program. The capability for installation of other subsystems (e.g., solar blankets, reflectors, power distribution lines and control equipment, microwave subarray hardware, etc.) on the structure must also be developed. Very little applicable data currently exist for this type of orbital and large-scale terrestrial construction and assembly. Test data are needed to validate operational requirements and cost estimates. Reference Figure 5.0-1.

TASK SUMMARY

Automated Construction

The overall objective of projects in this category is to demonstrate feasibility of high productivity space construction through test, analysis, and evaluation of critical construction equipment concepts and techniques. It also includes g ound demonstrations of SPS structure automated fabrication and assembly techniques.

Operations and Support

This task is intended to test and evaluate concepts for performance of critical space construction operations and functions including evaluation of construction support equipment concepts.

Hardware Handling and Installation

The objective is to test and evaluate concepts needed in constructing SPS systems such as solar cell blankets, concentrators, conductors, antenna gimbal joints, equipment modules, antenna subarrays, and fluid systems.

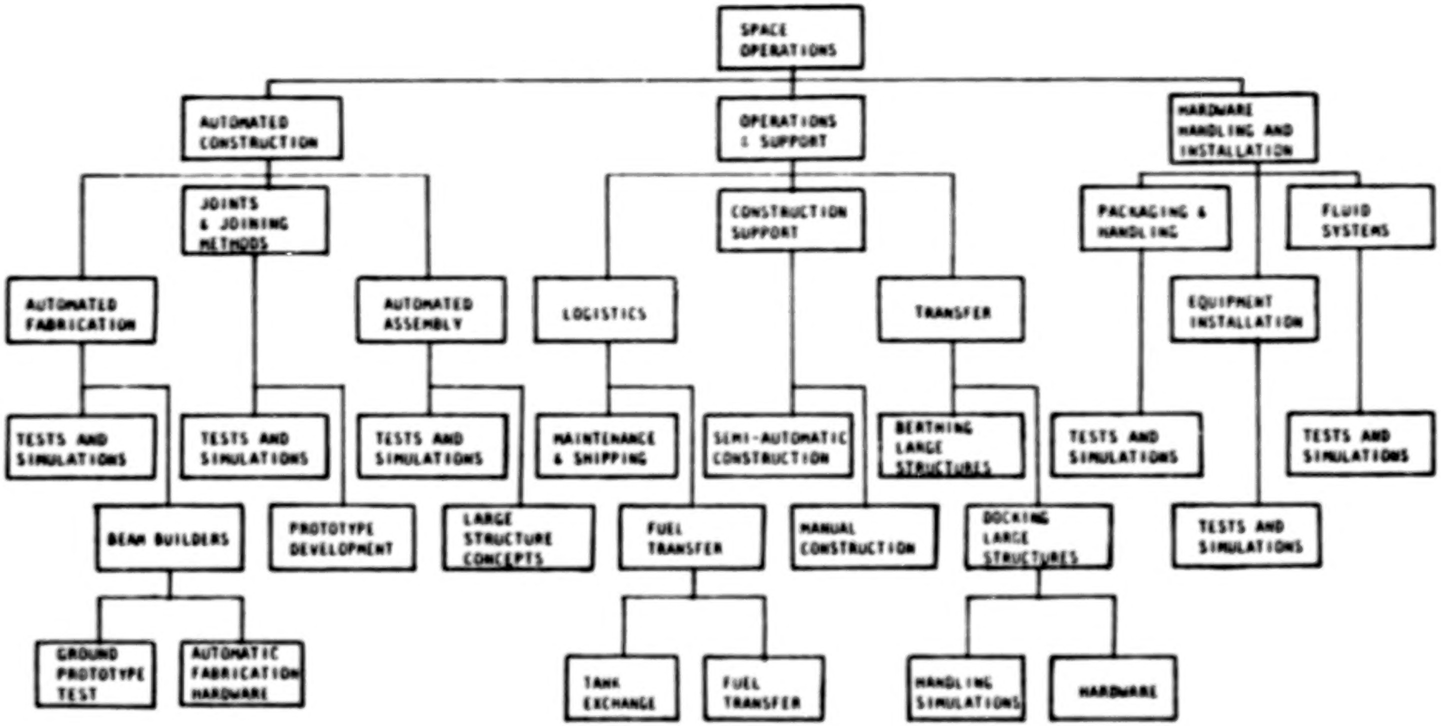


Figure 5.0-1. Space Operations Technology Tree

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: AUTOMATED CONSTRUCTION

JUSTIFICATION

Because of its massive size, the success of a Satellite Power System (SPS) is dependent on the ability to accomplish a major portion of the construction activity on orbit. On-orbit construction will necessarily require the early definition of construction equipment so that its early technology verification development activity can be defined and accomplished in a time frame compatible with other phases of the program. The beam builder is an example of on-orbit automated construction equipment. Almost every SPS study conducted by NASA and the aerospace industry has identified this piece of equipment as being necessary and requiring early development. The identification of other construction equipment, which may be even more complex than the beam builder, must be accomplished in the near-term future. To do this, an SPS configuration must be selected and subjected to a detailed construction scenario that will identify this equipment.

TECHNICAL OBJECTIVES

The overall objective of projects in this category is to demonstrate feasibility of high-productivity in-space construction through test, analysis, and evaluation of critical construction equipment concepts and techniques. It also includes ground demonstrations of SPS automated fabrication and structural assembly techniques.

TECHNICAL APPROACH

The relatively high cost of flight testing requires accomplishing as much development as possible on the ground. Engineering evaluation of much of the critical beam builder design can be accomplished with ground tests using a one-g beam builder configuration, special handling fixtures, an air bearing floor, and a water immersion facility. The beam builder development article is required to fabricate a long, continuous structural truss, allowing the evaluation of preprocessed materials packaging and dispensing; cap forming with heating, shaping, and cooling; synchronization and control of the truss elements; component handling and joining; and nondestructive quality control verification. Development of engineering and operational techniques for assembling more than one truss together to make a larger structural configuration can also be accomplished and simulated. Joint design and joining operations can be evaluated together with handling and assembly support equipment. These development tests will result in the engineering verification of a beam builder and associated assembly operations with sufficient confidence level to proceed to a flight verification experiment.

MILESTONE SCHEDULE

- Documentation supporting operations analysis, requirements definition —1984
- Beam builder ground tests and capability assessment—1985
- SPS ground test simulations of beam machine capability and supporting operations—joining, alignment—1986
- Preparations for flight test and space demonstration—1987

RESOURCE REQUIREMENTS

TBD

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: OPERATIONS AND SUPPORT

JUSTIFICATION

Operational logistics, construction support, and transfer of materials at the construction site are SPS requirements without precedent. Confidence in the ability to support automated fabrication and assembly is needed to define and validate the movement of systems, equipment, and fuelds in space; docking with large structures being assembled; and manual or semi-automated construction techniques.

TECHNICAL OBJECTIVES

Analyze, test, and evaluate concepts for performance of critical space construction operations and logistics support functions including the evaluation of construction support equipment and alignment techniques.

TECHNICAL APPROACH

Determine concepts, develop computer analyses and simulations for operational activities such as equipment transfer, berthing dynamics, and semi-automated construction techniques. Design and fabricate ground test construction support equipment. Conduct simulations of space operations and functions such as transport, handling, and processing in vacuum and zero-g simulation facilities.

MILESTONE SCHEDULE

- Operational concepts and support functions defined—1984
- Inital handling techniques for evaluation—1985
- Simulation and analysis of ground test activities—1986

RESOURCE REQUIREMENTS

TBD

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: HARDWARE HANDLING AND INSTALLATION

TECHNOLOGY REQUIREMENT

The SPS will require the deployment and installation of large area systems and modules such as solar blankets, concentrators (reflectors), and sub-arrays. Packaging and handling requirements also need definition. The technology requirement is for the analyses, concept definition, and ground test verification of identified methods.

TECHNICAL OBJECTIVES

To test and evaluate concepts needed in constructing/installing SPS systems such as solar cell blankets, concentrators, conductors, antenna gimbal joints, equipment modules, and antenna subarrays.

TECHNICAL APPROACH

The ground-based approach will be to identify and develop assembly techniques for other than structural components. Techniques for attaching hardware such as solar blankets, reflectors, power distribution lines, thrusters, and microwave components will be pursued. The development of electrical connectors suitable for orbital assembly operations is another area requiring identification. Packaging and deployment concepts for large area systems need evaluation plus sub-scale testing and simulation.

MILESTONE SCHEDULE

- Initial concept definitions—1984
- Sub-scale tests and simulations—1986

RESOURCE REQUIREMENTS

TBD

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TECHNOLOGY TITLE: SPACE TRANSPORTATION

TECHNICAL SUMMARY

The objective of this effort is to conduct critical early analyses and exploratory technology relating to the various transportation system elements, key technical issues resolution and fundamental technical feasibility. The tasks in this plan address critical systems and subsystems issues relative to earth to low-earth orbit and orbit-to-orbit transfer vehicles for both cargo and personnel. The transportation elements considered in this plan include: a Space Transportation System (STS) derived heavy lift launch vehicle (HLLV); dedicated SPS HLLV configurations; an electric orbital transfer vehicle (EOTV) for cargo transfer; and a personnel orbital transfer vehicle (POTV) for personnel/priority cargo transfer from LEO-TO-GEO and return. Systems and subsystems studies, computer analyses and modeling, experimental laboratory development, and engineering model evaluation are to be performed.

TASK SUMMARY

HEAVY LIFT LAUNCH VEHICLE DEFINITION

The potentially viable HLLV configuration options for SPS are numerous (i.e., one- or two-stage, ballistic or winged, etc.). Consequently, the technology plan has been structured such that primary emphasis is directed toward common technology needs of all potentially viable options, while maintaining a recognition of those unique technology advancement requirements which might yield the maximum gains for an SPS program.

Structural/Thermal Protection Systems

The materials required for the exterior of the vehicle must repeatably withstand an extreme thermal and stress environment. The materials available today which are capable of meeting some of these requirements cannot meet all of the desired criteria: coatings are subject to foreign object damage; embrittlement occurs after repeated exposure to environments resulting in reduced physical strength; the materials are heavy, costly, and/or in short supply. The development of thermostructural systems capable of taking full advantage of the potentially available advanced materials must be pursued. A wide variety of candidates is already available, but the relative merits of each must be determined.

Propellant Tank Insulation Systems

In order to meet the postulated operational requirements of the SPS transportation system, the cryogenic tanks of both the booster and the orbiter must be designed such that they require little or no inspection outside

normal maintenance cycles. Similar requirements are placed on the tank insulation also. The tanks of the present point design are identified as being non-integral structurally with the tank insulation system, permitting relatively easy inspection when required, but not allowing the buildup of icing on the external surfaces nor any cryopumping. A number of candidate insulation systems has been identified in past studies and, as in the case of the TPS, each has its own merits but none can completely satisfy SPS cryogenic tank insulation requirements. Materials and systems design technology must be pursued before any firm decision can be made on systems selection.

Liquid Rocket Engine Component Life Improvement

In order to minimize vehicle turnaround requirements and cost, all vehicle systems will require minimum inspection, maintenance, and replacement. This is especially true of the liquid rocket engines which are second only to the thermal protection system in turnaround operations requirements. Improvements in materials and design technology improvement in the critical areas of turbine pumps and seals, regulator valves, and precombustion chamber components are required to satisfy nominal turnaround operations and cost.

LOX/LH_2 Attitude Control Systems

Current liquid-fueled ACS technology is restricted almost exclusively to storable propellant types (i.e., hydrazine systems). In order to minimize the types of fuels required to satisfy SPS propulsion requirements and, consequently, operational complexity, cryogenic ACS systems are postulated. Minimal data are available relative to performance and life of cryogenic engines operating in the pulse mode. Breadboard engine testing is required to establish these data.

Self-Monitoring/Diagnostic Systems

A great dependence must be placed upon on-board monitoring and fault detection/isolation systems in order to preclude the requirement for ground interfacing and checkout requirements. All previous ground and flight performance data will be computer analyzed to determine performance trend data indicative of potential impending failures. The major element of ground operations is related to launch vehicle turnaround requirements. The high launch frequency demands an airline operations concept which, in turn, dictates vehicle design requirements which will result in the near-elimination of post-flight refurbishment and checkout other than that required for payload installation, mating, and fueling. Methods of implementation and types of diagnostic monitoring equipment must be evaluated and defined.

Advanced Engine Concepts

The availability of so-called exotic or highly innovative new propulsion concepts could offer significant improvements in performance, operations, and cost for an SPS program.

A horizontal takeoff heavy lift launch vehicle (HTO-HLLV) could utilize hydrogen fueled multicycle air-breathing engine systems (MC-ABES) during flight through the sensible atmosphere. The MC-ABES are required to efficiently operate over a Mach range from 0 to 7 and an altitude of 0 to 120,000 ft. The primary areas requiring analyses and technological advancement include engine cycle performance and lightweight fuel-cooled engine and inlet structures/components. The objective is to synthesize a MC-ABES with an installed minimum thrust/weight of 10 and an average net fuel specific impulse of approximately 4000 sec. The ABES cycles requiring evaluation include turbojet, air-turbo exchanger (air-turbo rocket) and ramjet.

A vertical takeoff single-stage-to-orbit HLLV could utilize a multimode (dual fueled) liquid rocket engine of the AGC expander type. Further technology developments are required before such an engine could be considered for the SPS program. Breadboard engine testing is required to provide performance and performance scaling data.

ELECTRIC ORBITAL TRANSFER VEHICLE DEFINITION

Independent of SPS assembly location, there is a significant demand for OTV transportation from LEO to GEO due to the magnitude of the SPS program. For the LEO-assembled SPS, hardware flights dominate the early years but in later years, logistics flights become a significant factor. Since propellant to support these OTV flights represents a significant portion of the total HLLV payloads, alternate advanced OTV concepts having high specific impulse appeared to be worthwhile candidates to satisfy cargo mass transfer requirements. An argon ion bombardment thruster system appears to be the best candidate to satisfy SPS requirements.

The unique technology requirement is in the primary area of ion engine development. The key requirement is in large size (1.0×1.5 m), high-current density (1000 A/m^2) thruster demonstration. Further analyses and demonstration testing of the "direct drive" concept, to minimize power processor weight and cost, are also required. Conventional power conditioners for ion bombardment thrusters regulate all supplies, serving as an interface between the power source (solar array) and the thrusters. Various so-called direct-drive concepts have been proposed in which some of the thruster supplies are obtained directly from the solar array. This approach reduces power conditioner mass, power loss, and cost, and improves propulsion system reliability.

PERSONNEL ORBITAL TRANSFER VEHICLE

The personnel orbital transfer vehicle (POTV) consists of that propulsive element required to transfer a personnel module (PM) and its crew/construction personnel from LEO to GEO. The POTV is a chemical (LOX/LH_2) rocket stage which is initially fueled in LEO and refueled in GEO for return to LEO.

The POTV shares common technology requirements with the HLLV (i.e., propellant tank insulation, engine component life, self-monitoring/diagnostic equipment, etc.), and can benefit from those technology programs implmented for the HLLV. A unique technology requirement of the POTV is in the area of orbital maintenance. Continuation of on-going orbital propellant transfer technology programs can satisfy this requirement.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: STRUCTURAL/THERMAL PROTECTION SYSTEMS

TECHNOLOGY REQUIREMENT

The materials which have been identified to date as being capable of withstanding the high temperatures of entry are generally very fragile, expensive, heavy, or rare, in any combination. Those materials which will have application to future lifting entry vehicle will have to overcome these shortcomings to be acceptable for the routine operations contemplated for the SPS HLLV transportation system.

STATE OF THE ART

The thermal structural system to be ultimately selected must satisfy requirements which are basically the same as the thermal structural systems in use today. The significant change, of course, is in the operating environment. This environment is much more stringent than is experienced today in any aircraft-like systems other than the Space Shuttle orbiter. It will eventually require the establishment of new or highly modified specifications to augment those in use today.

TECHNICAL OBJECTIVES

To identify and test a range of structural and TPS materials concepts that will meet the rigorous weight and reuse/refurbishment requirements necessary for the economical operation of a heavy lift launch vehicle. This will faciltate an orderly selection of a structural/TPS approach for the HLLV.

APPROACH

The development of thermostructural systems capable of taking full advantage of the potentially available advanced materials must be intensively pursued. A wide variety of candidates is already available, but the relative merits of each needs to be determined. The following subtasks will be performed.

- Identify RSI, honeycomb, and composite materials that might be applicable for a heavy lift launch vehicle. Identify the critical properties requiring test.
- Test the materials and document the properties.
- Fabricate structural elements having the expected shapes, thicknesses, etc., that would be present in the HLLV and test.
- Conduct experiments associated with novel approaches to bonding honeycomb materials.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN	TASK TITLE: STRUCTURAL/THERMAL PROTECTION SYSTEMS

MILESTONE SCHEDULE	FY →	1981	1982	1983	1984	1985	1986	1987
IDENTIFY RSI MATERIALS/CONCEPTS								
TEST & DOCUMENT MATERIALS PROPERTIES								
FABRICATE & TEST TYPICAL STRUCTURAL ELEMENTS								
ADVANCED BONDING APPROACHES								

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: PROPELLANT TANK INSULATION SYSTEMS

TECHNOLOGY REQUIREMENT

In order to meet the postulated operational requirements of the SPS transportation system, the cryogenic tanks of both the booster and the orbiter must be designed such that they require little or no inspection outside normal maintenance cycles. Similar requirements are placed on the tank insulation also.

STATE OF THE ART

A number of conceptual insulation systems have been identified in past studies. Each has its own relative merits and none are completely satisfactory in all respects. An extensive conceptual development program is necessary before any firm design decisions can be made.

TECHNOLOGY OBJECTIVES

To identify a cryogenic tank insulation system capable of meeting the rigorous reuse/refurbishment requirements necessary for the economical operation of SPS transportation elements.

APPROACH

All aspects of cryogenic tank design must be evaluated and resolved. This includes the analysis of integral and non-integral tanks, insulation techniques, and operational utility. The following insulation systems will be evaluated for applicability:

Evacuated System (Vacuum)

- Compressed superinsulation

Purged Systems

- Quartz fiber purged with helium
- Marshield purged with helium
- Aluminum shields with dimpled fiberglass spacers
- Polyurethane foam

Sealed Systems

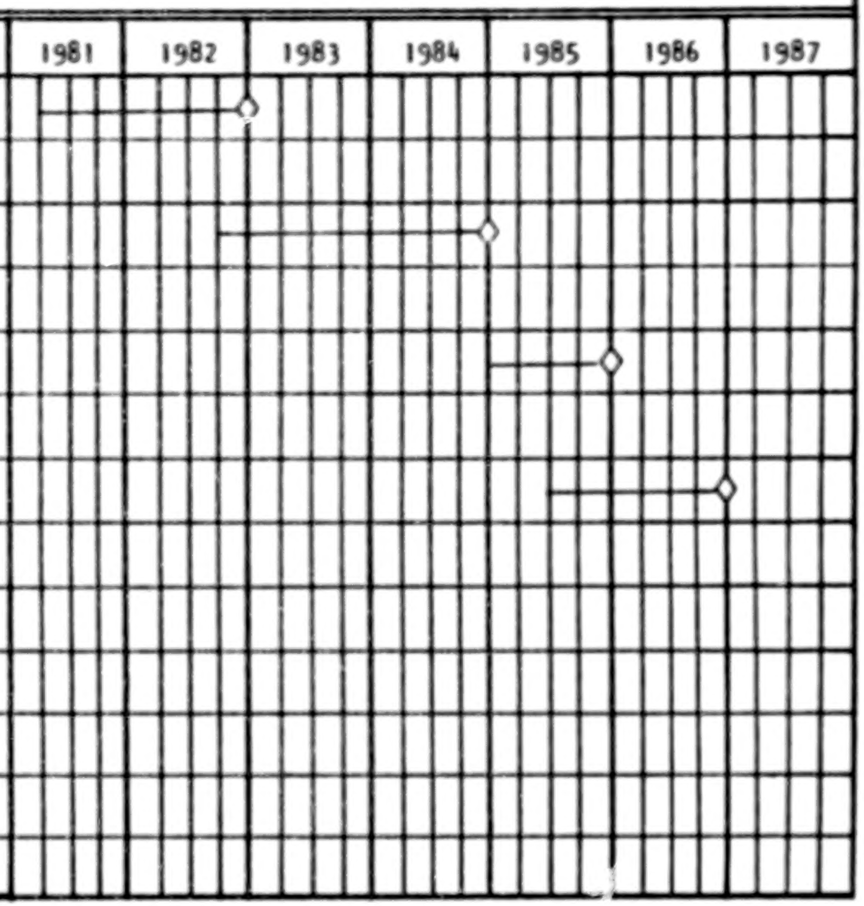
- Polyurethane foam (Freon or CO_2 blown)
- Mylar honeycomb sandwich filled with polyrethane foam
- Phenolic fiberglass honeycomb sandwich
- Corkboard
- Polyimide foam

Sealed and Purged Systems—The sealed systems are used with a quartz-fiber blanket purged with helium or nitrogen.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: PROPELLANT TANK INSULATION SYSTEMS

MILESTONE SCHEDULE — FY →



INSULATION SYSTEMS ANALYSES

MATERIALS TESTING

INSULATION SYSTEMS DESIGN CONCEPTS

INSULATION SYSTEMS TESTING

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: SPS TRANSPORTATION SYSTEM—LIQUID ROCKET ENGINE AND FUELS

TECHNOLOGY REQUIREMENT

The use of LOX/hydrocarbon liquid rocket engines for first-stage HLLV operation has been shown to be most cost effective. Insufficient data are available to establish engine specific fuel and cooling requirements.

STATE OF THE ART

LOX/HC engines have employed the gas generator cycle for fuel flow into the engine with low combustion chamber pressures. More efficient LOX/LH_2 engines, such as the SSME, utilize staged combustion techniques and high combustion chamber pressures.

TECHNICAL OBJECTIVES

Conduct the required propulsion technology necessary to develop the required data base to allow for the initiation of an engine development program for a LOX/hydrocarbon (RP1 and/or methane) engine that utilizes high chamber pressures. Cooling, combustion, and life considerations are some of the areas that must be examined.

APPROACH

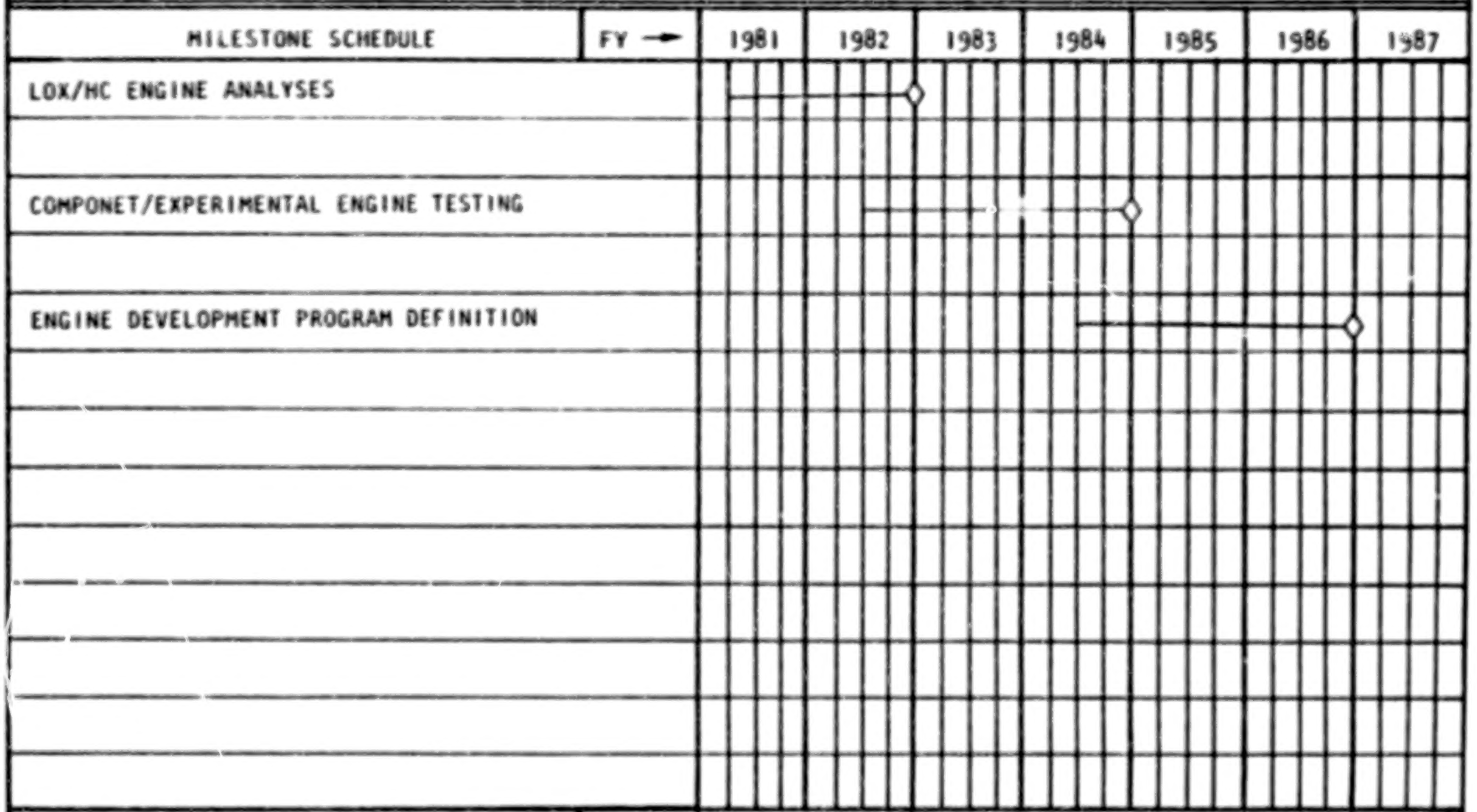
1. Conduct LOX/HC engine studies to compare gas generator to stage combustion power cycles for the various hydrocarbon fuels (RP, methane, propane). This analysis will compare the performance and cooling and identify the required general technology (turbomachinery bearings, seals, and controls).

2. Conduct component/experimental engine verification for the candidate engine types.

3. Define proposed experimental engine programs.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: LIQUID ROCKET ENGINE AND FUELS



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: LOX/LH_2 ATTITUDE CONTROL SYSTEMS

TECHNOLOGY REQUIREMENT

Establish performance, design, and operating characteristics of cryogenic fueled liquid rocket engines when operating in a pulse mode.

STATE OF THE ART

Current liquid fueled ACS engine technology is restricted to storable propellant engine types (i.e., hydrazine systems).

TECHNOLOGY OBJECTIVES

To determine appropriate design parameters and performance of LOX/LH_2 engines under pulse mode operation in sufficient depth to minimize uncertainties in scaling and extrapolation of existing data.

APPROACH

Analytical studies will be required to define a breadboard engine/component study program. These analyses will include valving, power cycle, cooling, etc., and their impact on engine performance. Limited breadboard testing of LOX/LH_2 engines operating in a pulse mode will be conducted.

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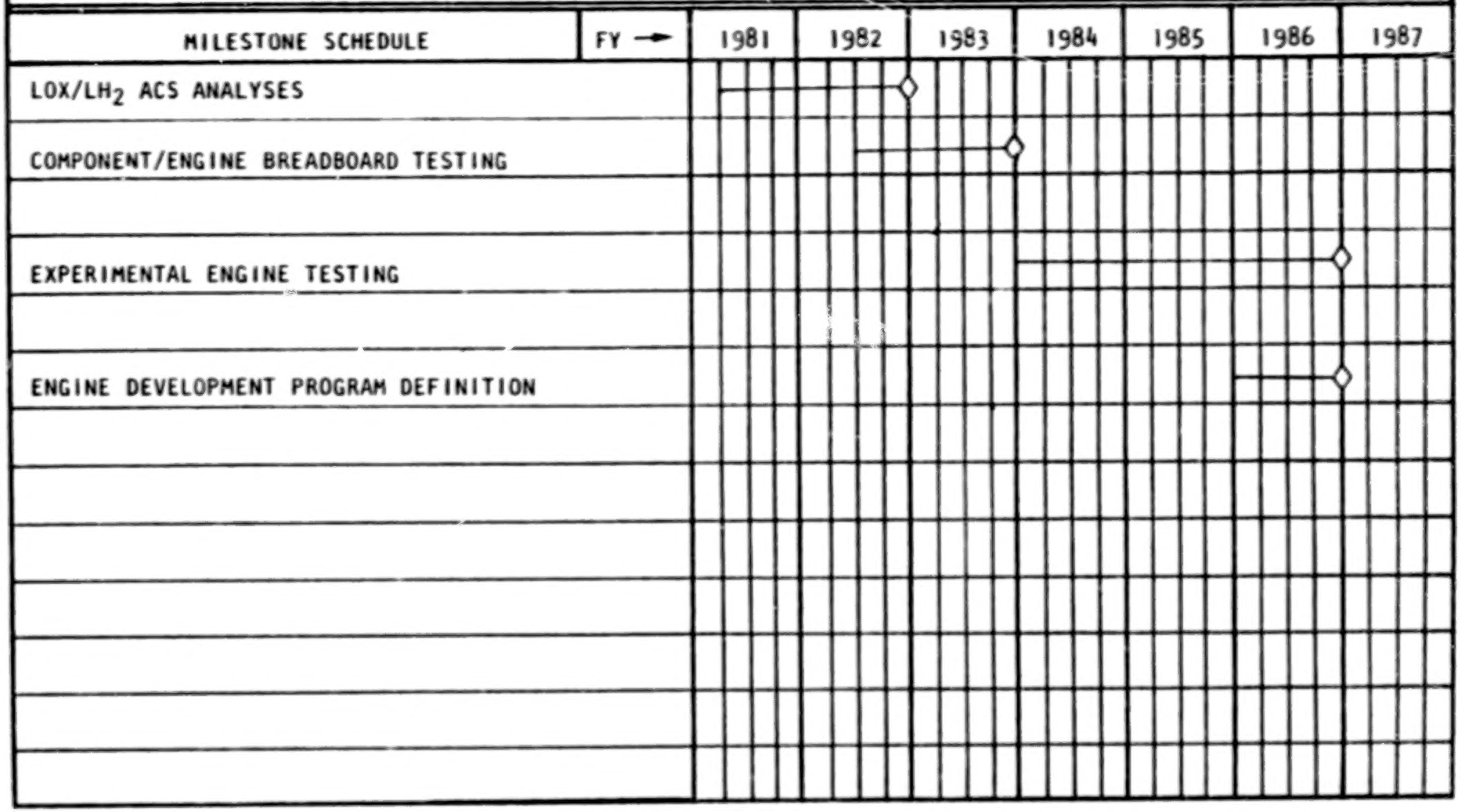
SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: LOX/LH_2 ATTITUDE CONTROL SYSTEMS



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: SELF-MONITORING/DIAGNOSTIC SYSTEMS

TECHNOLOGY REQUIREMENT

The major element of ground operations is related to launch vehicle turn-around requirements. The high launch frequency demands an airline operations concept which, in turn, dictates vehicle design requirements which will result in the near-elimination of post-flight refurbishment and checkout other than that required for payload installation, mating, and fueling.

STATE OF THE ART

Current airline operations utilize this approach.

TECHNOLOGY OBJECTIVES

Identify on-board monitoring and fault detection/isolation systems in order to preclude the requirement for ground interfacing and checkout requirements. Identify ground and flight performance data requiring computer analyses to determine performance trend data indicative of potential impending failures.

APPROACH

Evaluate each flight subsystem to determine potential failures and effects.

Identify critical fault detection/isolation and monitoring requirements for each subsystem.

Synthesize self-monitoring/diagnostic systems to satisfy SPS transportation element requirements.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: SELF-MONITOR/DIAGNOSTIC SYSTEMS

MILESTONE SCHEDULE	FY →	1981	1982	1983	1984	1985	1986	1987
PERFORM SUBSYSTEM FMEA								
IDENTIFY DETECTION/ISOLATION REQUIREMENTS								
SYNTHESIZE SM/DIAGNOSTIC SYSTEMS								

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: SPS TRANSPORTATION SYSTEM/MULTICYCLE AIRBREATHING ENGINE SYSTEM (MC-ABES)

TECHNOLOGY REQUIREMENT

The SPS earth to LEO operational transportation system is a major contributor to overall program cost. The development of a suitable MC-ABES could meet the needs of a fully recoverable/reusable horizontal earth launch vehicle which would drastically reduce overall SPS transportation systems and operations costs. An installed engine T/W of approximately 10 is required.

STATE OF THE ART

Hydrogen fueled MC-ABES engines have been synthesized and tested over a decade ago which are capable of installed thrust/weight ratios in the order of six. During the past decade, no significant technology development has been pursued in this area.

TECHNICAL OBJECTIVES

Synthesize and analyze MC-ABES with a minimum thrust/weight (installed) of 10 to 1 and a minimum average net specific impulse of 4000 sec.

Identify specific MC-ABES components and subsystems requiring technology development.

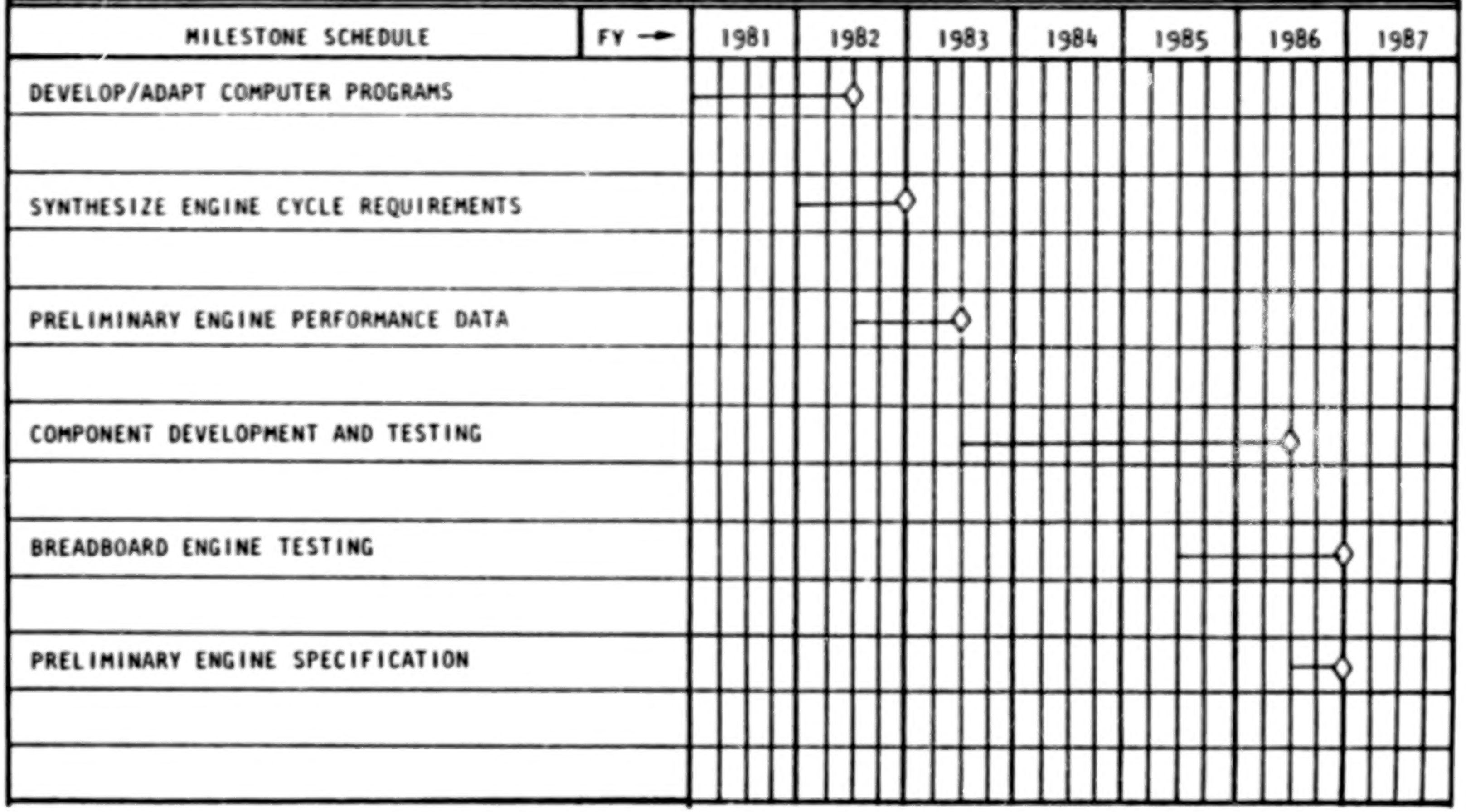
Initiate critical component development and testing programs. Components or subsystems will be at the laboratory or "breadboard" level.

APPROACH

Develop/adapt MC-ABES cycle performance computer programs. Based upon the computer analyses, synthesize a MC-ABES capable of providing the required thrust and performance. Conduct performance sensitivity analyses and identify critical areas and components requiring technological development. Prepare component and subsystem design, development and test plans and requirements. Conduct laboratory and/or breadboard model testing to the level required to provide the necessary technological base to assure the successful design/development of the required flight hardware prototype. The design and development of the flight hardware is not a part of this task. Prepare a preliminary MC-ABES specification.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: MULTI-CYCLE AIRBREATHING ENGINE SYSTEMS



SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: BALLISTIC RECOVERY OF LIQUID ROCKET STAGES

TECHNOLOGY REQUIREMENT

The precursor phase of the SPS program will require the use of an interim HLLV concept, an STS derived HLLV. A promising derivative replaces the solid rocket booster (SRB) of the STS with liquid rocket boosters (LRB). Liquid boosters have never been routinely recovered and reused after a landing at sea; therefore, the behavior of structures and cryoinsulation during the landing/recovery phase is unknown.

STATE OF THE ART

The routine recovery and reuse of the SRB are planned for the Shuttle STS program. Recovery systems have been designed and scale-model tests performed.

TECHNICAL OBJECTIVES

To test structural concepts under the anticipated environments (including salt water corrosion) to determine what damage, if any, results and the required refurbishment of liquid rocket boosters.

APPROACH

1. Screen the candidate recovery concepts to be able to select the more promising materials and structural arrangements.
2. Conduct tests including subscale drop tests to determine feasible design approaches.
3. Identify potential environmental protection requirements.
4. Identify potential refurbishment and turnaround requirements.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: BALLISTIC RECOVERY OF LIQUID ROCKET STAGES

MILESTONE SCHEDULE	FY →	1981	1982	1983	1984	1985	1986	1987
SCREEN CANDIDATE CONCEPTS								
MATERIALS/COMPONENT TESTING								
SUBSCALE DROP TESTING								
IDENTIFY REFURBISHMENT REQUIREMENTS								
IDENTIFY SYSTEM DESIGN REQUIREMENTS								

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ON-ORBIT PROPELLANT TRANSFER

TECHNOLOGY REQUIREMENT

Transfer of cryogenic propellants from a transport vehicle either to an orbit-to-orbit heavy cargo vehicle, a space base or a chemical orbital transfer vehicle will be an SPS requirement.

STATE OF THE ART

Analytical studies of the general problems only have been conducted to date. Zero-g transfer of propellants has been accomplished with bladder systems only.

TECHNOLOGY OBJECTIVES

The capability to transfer propellants while in a zero-g environment must be demonstrated so that the proper decision-making can take place with regard to propellant types, transfer losses and design impacts to the OTV's and transfer vehicles.

APPROACH

1. Analyze propellant transfer requirements and define technology and components required to implement propellant transfer.

2. Design and fabricate components—Develop test procedures.

3. Test the components.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

<u>TASK TITLE:</u> ON-ORBIT PROPELLANT TRANSFER

MILESTONE SCHEDULE	FY → 1981	1982	1983	1984	1985	1986	1987
ANALYZE & DEFINE TRANSFER REQUIREMENTS							
DESIGN & DEVELOP TEST PROGRAM							
COMPONET/LABORATORY TESTING							
ORBITAL TRANSFER TESTING (SORTIE)							

CONTENTS

Section | Page

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ELECTRIC THRUSTERS AND POWER PROCESSING

TECHNOLOGY REQUIREMENT

The EOTV argon ion propulsion system can only operate efficiently (competitively and advantageously) if refurbishment requirements can be minimized. It appears from work done at LeRC that thruster modules can be designed that will operate for decades without excessive deterioration, or a need for refurbishment, except for the accelerating grid sets. The grids are subject to positive ion bombardment, etc., and will require periodic refurbishment. A potential redesign of thruster modules may be required. This involves not only removable grid sets, but also possibly new materials, laboratory models, and supporting tests.

STATE OF THE ART

Electric argon ion thrusters up to 30 cm in diameter having current densities in the order of 100 A/cm^2 have been successfully tested over long periods of operation.

TECHNICAL OBJECTIVES

Complete an EOTV mission analysis that reveals the set of desired thruster operating characteristics; i.e., specific impulse, thrust, trip time, fleet size, payload, electrical power profiles, and refurbishment cycles.

Conceptually design and size thrusters that satisfy the required thruster characteristics of the mission analysis.

Design and verify, with a simulated arrangement, a practical means of replacing thruster grids (several at one time) with the use of manipulator arms or some other arrangement.

Design and build a laboratory thruster module (one or more as required) which incorporates the refurbishable grid system selected from the simulated arrangement.

Test the thruster module to establish thrust, beam divergence, effectiveness of beam neutralization, and grid deterioration rates, etc.

APPROACH

1. Determine the preferred set of thruster operating characteristics, i.e., accelerating voltage (specific impulse), beam current (thrust), trip times (LEO to GEO, GEO to LEO), refurbishment cycles, solar blanket BOL power, mean electrical output, annealing cycles and methods, payload per EOTV trip, number of HLLV launches per SPS in GEO, thruster lifetime, etc.

2. Design and develop, possibly subscale, electric propulsion components and subsystem concepts for technological demonstrations in the following areas:

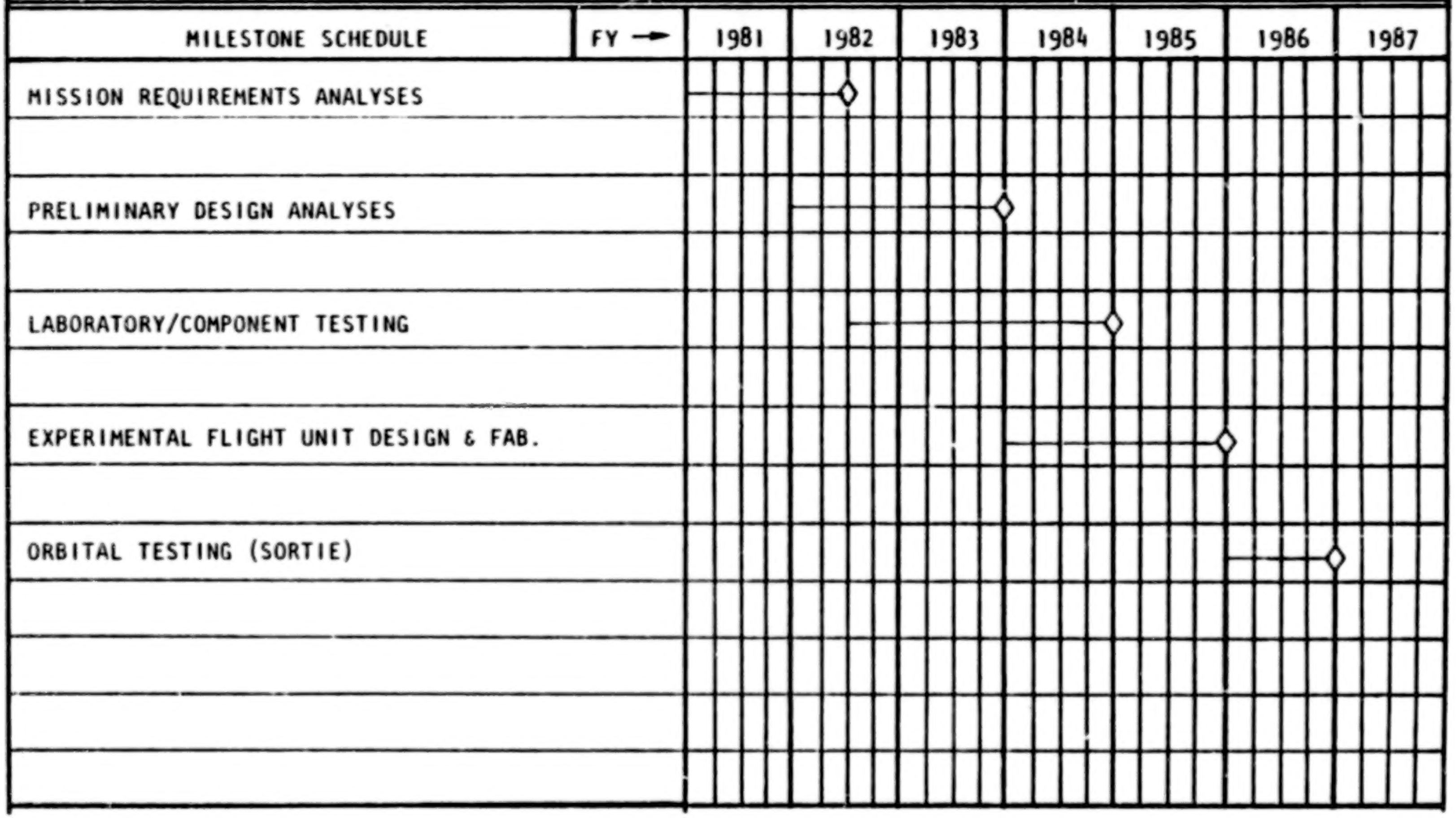
   - Large-diameter, high-input power ion thrusters using noble gases, i.e., argon
   - Operating voltage requirements (LEO/GEO plasma interaction constraints)
   - Power supply and distribution—advanced power processing concepts (e.g., direct drive)
   - Thermal control concepts
   - Instrumentation and control
   - Approaches to minimize specific mass

3. Demonstrate lifetime and/or reusability by:

   - Experimentally developing long-life components (grids, cathodes, etc.)
   - Simulating flight environmental conditions (on/off cycles due to shadow)
   - Subjecting test specimens to the plume environment such that erosion effects might be determined or avoided.

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

TASK TITLE: ELECTRIC THRUSTERS & POWER PROCESSING



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Marshall Technical Monitor: Charles H. Guttman
Volume V of the Final Report on Exhibit D

16. ABSTRACT

Studies of the Satellite Power System (SPS) concept have attested to the technical feasibility of solar power stations located in space and to their potentially economic advantages as compared with candidate earth-based energy systems in the calendar period, 2000 - 2030. Although overall success of SPS development is possible over a range of performance and design levels, it is necessary to define attainable performance parameters for the development of SPS specifications and design requirements through a confirmation of technology advancement requirements.

In order to continue with various SPS concept definition studies, knowledgeable extrapolations of the current state of technology, the degrees of improvement in technical performance, and the expected reductions in cost all require further analysis to identify the degree of technical risk. On this basis, planned experiments and exploratory technology development activities would reduce this uncertainty and improve the levels of confidence for system design.

This volume defines just such a series of requirements. It presents guidelines and ground rules followed in the development of requirements for the SPS. Development planning objectives are specified in each of these areas, and evolutionary SPS program scenarios are described for the various concepts studied during this past one-year contract. Program descriptions are presented as planning packages of technical tasks, and schedule phasing. Each package identifies the ground-based technology effort that will facilitate SPS definitions, designs, development, and operations.

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